NAVAL POSTGRADUATE SCHOOL
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THESIS

NUCLEATE BOILING CHARACTERISTICS OF R-113 IN A SMALL ENHANCED TUBE BUNDLE

by

Scott V. Chilman

September 1991

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Thesis Co-Advisor	S. B. Memory

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Nucleate Boiling Characteristics of R-113 in a Small Enhanced Tube Bundle

by

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Lieutenant, United States Navy
B.S.M.E.T., California Maritime Academy, 1983

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ABSTRACT

Heat transfer tests were carried out using a small enhanced tube bundle in a pool of R-113. By accurately instrumenting five tubes within the bundle, both the convective and nucleate boiling regions were studied in detail, with emphasis on the 'bundle' effect (i.e. the effect of lower tubes in operation on upper tubes within the bundle). In addition, the effect of surface history and pool height on nucleation site activation/deactivation was studied to see how this affects the overall heat transfer and in particular, the shape of the hysteresis loop. From the results, recommendations can be made to improve start-up procedures on shipboard AC systems.

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NOMENCLATURE

SYMBOL	UNITS	NAME/DESCRIPTION
Aas	V	Voltage output from current sensor
A_c	m^2	Tube-wall cross sectional area
A_s	m^2	Area of heated surface
C_p	J/kg K	Specific heat
D_i	m	Inside tube diameter
D_o	m	Outside tube diameter
D_{tc}	m	Thermocouple location diameter
fpi		Fins per inch
g	m/s^2	Gravitational acceleration
h	W/m^2 K	Heat transfer coefficient of enhanced tube surface
h_b	W/m^2 K	Heat transfer coefficient of tubes unheated ends
ht	m	Height of liquid column above a instrumented tube
k	W/m K	Thermal conductivity of refrigerant
k_{cu}	W/m K	Thermal conductivity of copper
L	m	Heated length of the tube
L_u	m	Unheated length of the tube
L_c	m	Corrected unheated length of the tube
n	1/m	Parameter in calculation of q_f
Pr		Prandtl number
p	m	Perimeter of the tube outside surface
ΔP	Pa	Hydrostatic pressure difference between tube and liquid free surface

q	W	Heat transfer rate
q''	W/m^2	Heat flux
q_f	W	Heat transfer rate from unheated smooth tube ends
t	m	Thickness of the tube wall
T	C	Temperature
T_{film}	C	$(Tsat_c + \overline{T}wo) / 2$, Film temperature
T_{filmK}	K	Film thermodynamic temperature
Tld1	C	Liquid temperature reading from T(3)
Tld2	C	Liquid temperature reading from T(4)
Tsat	C	Saturation temperature
$Tsat_c$	C	Corrected saturation temperature due to hydrostatic pressure difference
$\overline{T}wi$	C	Average inside wall temperature
$\overline{T}wi\text{-}K$	K	Average inside wall thermodynamic temperature
$\overline{T}wo$	C	Average outside wall temperature
Vas	V	Voltage output from voltage sensor
α	m^2/s	Thermal diffusivity
β	1/K	Thermal expansion coefficient
μ	kg/m s	Dynamic viscosity of liquid
ν	m^2/s	Kinematic viscosity of liquid
ρ	kg/m^3	Density of liquid
Φ	C	Fourier conduction term
θ_b	C	$\overline{T}wo - Tsat_c$, Wall Superheat

ACKNOWLEDGEMENTS

I would first like to express my appreciation to all those who supported me. Especially, Professor Marto who provided inspiration and guidance from the very beginning and also Professor Memory whose software writing expertise, willingness to assist, and accurate guidance made this research a great learning experience.

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I. INTRODUCTION

A. BACKGROUND

In September 1987, due to the pressing environmental issues of ozone depletion and global warming, an international conference was held in Montreal, Canada. This conference was viewed by many as a major step toward correcting the critical environmental problems facing the world today. Specifically, one of the problems addressed was chemical products damaging the protective bubble we live in. This bubble or thin layer is known as the ozone layer, and is what makes the earth's atmosphere habitable and hence unique from any other known planet. Without this protective layer, the earth's climate would not support life as we know it today. Protecting this ozone layer from chemical destruction is paramount.

A group of chemicals that deplete the ozone layer is chlorofluorocarbons (CFCs). CFCs are manmade chemicals of chlorine, fluorine and carbon and were developed almost 60 years ago by General Motors. They are unique in that they have a combination of desirable properties not often found in chemistry; low in toxicity , non-flammable, non-corrosive, non-explosive, extremely stable and compatible with many other materials. However, it is this extreme stability which causes problems to the ozone layer, because they only break down in the upper atmosphere (stratosphere) when subjected to intense ultraviolet radiation. This breakdown produces chlorine which has been linked to the depletion of the earth's protective ozone layer. A chlorine atom destroys an ozone molecule (0_3) by reacting with it and converting it to an ordinary oxygen molecule (0_2) and carbon monoxide. More disturbing is the fact that the chlorine atom survives the ozone-destroying reaction and is free to repeat the process - one CFC molecule being able to destroy 100,000

ozone molecules. Unfortunately, a typical chlorine molecule can survive for up to 100 years, so a major problem does exist.

Armed with these facts, 24 nations (representing the United Nations Environment Program (UNEP)) met and signed the Montreal Protocol in 1987. They discussed substances that deplete the ozone layer [Ref. 1] and called for a near-term freeze on the production and consumption of these substances. To be more specific, it required production of these chemicals to be cut back to 1986 levels followed by a two-phased reduction culminating in cutbacks of 50% by mid-1998; this came into effect on July 1, 1989. In 1990, a progress meeting was held in London where UNEP delegates agreed to completely phase out all CFCs by the year 2000 [Ref. 2]. This was a needed, but worrisome change for the U.S. Navy as they use a number of different CFCs for various refrigeration and solvent/cleaning needs. One such need is the approximately 1850 shipboard air conditioning (AC) plants presently using CFC-12 (in reciprocating compressor plants) and R-114 (in centrifugal compressor plants). These AC plants not only provide personal comfort, but cool vital electronic components,weapons systems and other auxiliary equipment.

To comply with the Montreal Protocol and U.S. legislation, the Mechanical Systems Branch/(Code 2722) at David Taylor Research Center (DTRC) is pursuing research aimed at eliminating shipboard use of CFCs. As mentioned by Krinsky and Noel [Ref. 3] this research is to be completed in three phases:

1. In the short term, to identify suitable alternative ozone-safe chemicals to directly replace CFC-12 and CFC-114. In order to do this, the heat transfer characteristics must be similar to the existing refrigerants in place and hence the need for a database exists for current refrigerants (i.e. R-114, R-12, R-113) so that they can be compared to the new proposed refrigerants.

2. In the longer term, to research, develop and test substitute chemicals and alternative technologies to replace existing CFC uses.

3. To implement new cooling system technologies into the Fleet which do not depend on CFCs or their replacements. One such technology under investigation at the Naval Postgraduate School is thermoacoustic refrigeration, which uses sound waves to compress and expand harmless gas molecules (such as helium) inside a tube.

The purpose of this thesis is to supplement DTRC's research on alternatives to CFCs by establishing baseline nucleate pool boiling data of R-113 from a small bundle of enhanced tubes representing a section of a flooded evaporator . Emphasis is placed on surface history affecting activation/deactivation of nucleation sites, hysteresis, and the affect of varying evaporator pool height. The data obtained are expected to serve as reference data for comparison with future proposed refrigerants from bundles of both smooth and enhanced tube surfaces. It is felt that what is learned from this thesis about the characteristics of R-113 can be applied to any general refrigerant and can help the Navy design future AC systems using alternative chemicals.

B. OBJECTIVES

The objectives of this thesis are as follows:

1. Understand in greater detail both the convection and nucleate pool boiling phenomena and hysteresis effects within a small enhanced tube bundle.

2. Vary the evaporator pool height above the tube bundle to see how this effects nucleation site activation and general evaporator performance.

3. Investigate the effect of surface history on nucleation site activation/deactivation.

4. Compare data with similar studies (i.e. same fluid or tube) done at the Naval Postgraduate School.

II. LITERATURE SURVEY

A. GENERAL INTRODUCTION

Due to the desirability of operating many engineering devices in the nucleate boiling region, many types of enhanced tubes are being studied. Nishikawa et al. [Ref. 4] noted that there are two primary ways to increase the heat transfer performance of a boiling tube. The first was to decrease the wettability of the fluid in which you are immersed. They suggested using a Teflon coating on the boiling surface. However, this is not very effective for refrigerants as they are very highly wetting on any surface and fill the cavities of the Teflon surface. The second way proposed was to manufacture a tube with many re-entrant cavities, thereby trapping the vapor and keeping the nucleation sites active. These re-entrant cavities are designed such that if one site is activated, neighboring sites will soon follow and cause the entire tube to nucleate almost instantaneously due to the interconnecting passageways. There are now many such tubes with re-entrant cavities on the market.

The two main types of reboilers analyzed today are kettle reboilers and full bundle boilers. The difference is described in detail in Payvar [Ref. 5]. To summarize, in the kettle type reboiler the tube bundle only occupies the middle lower portion of the evaporator leaving large areas on the sides of the bundle for fluid circulation. The full bundle boilers occupy the whole cross section of the lower half of the evaporator shell. As can be reasoned from these definitions, circulation patterns are very different for the two types of boilers.

The following is a brief summary of the work done on the bundle apparatus at the Naval Postgraduate School:

1. T.J. Murphy, September 1987 [Ref. 6]

   • Designed System

   • Conducted Preliminary Operation

2. C.L. Anderson, June 1989 [Ref. 7]

   • Tested Smooth Tubes, R-113

   • Tested Smooth Tubes, R-114/Oil

   • Tested Finned Tubes (19 fpi), R-114/Oil

3. N. Akcasayar, December 1989 [Ref. 8]

   • Tested Finned Tubes (19 fpi), R-114/Oil

   • Tested High Flux Tubes, R-114/Oil

4. H. Eraydin, December 1990 [Ref. 9]

   • Tested High Flux Tubes, R-114/Oil

   • Tested Turbo-B Tubes, R-114/Oil

B. EXPERIMENTAL AND THEORETICAL STUDIES

In the literature survey, no papers were found on the Turbo-B tube operating in a bundle or how surface history affects Turbo-B nucleation site activation/deactivation. In addition, no information was found on varying the pool height above the bundle to see how this affects nucleation site activation and general evaporator performance. These areas could be very important to the U.S. Navy as well as to industry and could cause the startup procedure of refrigeration units to be altered, thus emphasizing the need for the objectives of this thesis.

In the past decade, there have been significant improvements made to tube surfaces and in understanding the natural convection and nucleate boiling regions for a single tube apparatus and several correlations have been adapted. However, the tube bundle opens a new arena of topics.

Yilmaz and Westwater [Ref. 10] studied the effect of velocity past a smooth tube and how it effects the heat transfer performance. They used a 6.5 mm diameter tube in R-113. They found that with an increase in velocity, the heat transfer performance of the tube was better.

Cornwell and Schuller [Ref.11] stated that the increases in heat transfer coefficient found by Yilmaz and Westwater could not entirely be explained by the increase in velocity past the tube. Therefore, they decided to conduct a photographic study of boiling R-113 in a bundle at one atmosphere. Their study used 241 electrically heated tubes, 19.1 mm in diameter and arranged in a square in-line pitch of 25.4 mm, giving a pitch-to-diameter ratio of 1.33. They found that the bubbles leaving the lower tubes in the bundle impacted and caused a sliding motion around the upper tubes. Cornwell and Schuller attribute the increase in the upper tubes heat transfer performance on this impact and sliding motion of bubbles from lower tubes. Cornwell and Schuller also showed that the heat transfer coefficient was the highest for the top tube in the bundle and decreased as one moved down the bundle; the difference was as much as four times. Cornwell [Ref. 12] later found that in the nucleate boiling region, sliding bubbles and liquid forced convection could account for all the heat transfer in the top of the bundle.

Chan and Shoukri [Ref. 13] studied the boiling characteristics of a small enhanced multitube bundle in a pool of R-113. The rectangular bundle had a vertical pitch of 23.8 mm and a horizontal pitch of 31.75 mm. From there studies, they concluded that the convective contribution is highest for tubes near the top of the bundle due to the increased quality and fluid velocity across these tubes. They also noted at lower heat fluxes, the convective effects dominate whilst for higher heat fluxes, the primary mode of heat transfer was nucleate boiling. At high heat fluxes there are numerous active nucleation sites and a high bubble generation rate which decreased the influence of rising bubbles generated from

tubes below. They also found that the convective effect from a boiling tube below an upper tube in a bundle has less of an effect as it gets farther from the tube of interest.

A study by Bergles et al. [Ref. 14] showed that if a tube is on the verge of nucleation, it burst into nucleation if tapped. This test was repeated many times with the same results. Several other experimenters using different tubes, refrigerants, and bundle arrangements, have also shown the influence of tube position on heat transfer performance in the bundle. Wallner [Ref. 15] used a smooth tube bundle with both square and triangular geometric arrangements giving pitch-to-diameter ratios of 1.33 to 1.5 respectively. He found a 50 percent increase in the heat transfer coefficient over a single tube for tubes near the top of the bundle.

Fujita et al. [Ref. 16] used both smooth and enhanced tubes to study the effects of tube position, distribution of heat flux, and system pressure changes (0.1 to 1 MPa) within the bundle. They used a triangular tube arrangement with R-113. In these tests, they reported similar results as above with higher tubes giving improved performance. The enhancement in heat transfer again was believed to be caused by bubbles generated from the tubes below.

Webb et al. [Ref. 17] pointed out that in air conditioning applications, the refrigerant typically enters the bundle with a 15 percent quality. With this entering quality into the bundle, it simulates the effect of lower tubes activated in the bundle and thus will improve the performance of the entire bundle. Furthermore, the boiling mechanism for a flooded evaporator is very different from the kettle type evaporator and therefore it is very hard to formulate and evaluate a theoretical model for a bundle.

Leong and Cornwell [Ref. 18] looked at the same representative slice of a flooded evaporator that Cornwell and Schuller [Ref. 11] and Cornwell [Ref. 12] studied. They

concluded that the heat transfer coefficients were the highest at the top of the bundle and decreased in performance as you went down the bundle.

Based on the above-mentioned studies, all experimenters seem in agreement, independent of the fluid or tube used in the bundle, that the presence of boiling lower tubes causes a convective flow in the evaporator that gives rise to an increase in the heat transfer coefficient on the upper tubes.

III. EXPERIMENTAL APPARATUS

A. TEST APPARATUS OVERVIEW

The whole experimental apparatus including the auxiliary equipment and the evaporator/condenser test apparatus used during this investigation is shown in Figure 1. The following is only a general description of the whole experimental apparatus. A more detailed look at the condenser and evaporator is provided in Section D. Further information about the apparatus is provided by Murphy [Ref. 6] and Anderson [Ref. 7].

Looking at Figure 1, the apparatus uses three closed loops. The first loop consists of an 8 ton refrigeration unit located outside the laboratory which is used to cool an ethylene glycol/water mixture. The second loop is the ethylene glycol/water mixture flowing through the condenser. This flow rate through the condenser was delivered by two pumps which could be operated independently or together; this coolant mixture condenses the refrigerant vapor in the condenser and maintains system pressure. Pump number one provided coolant flow through the four test tubes as well as to one of the auxiliary coils. Pump number two provided coolant through a manifold which distributed the coolant to the remaining four coils in the condenser. The third loop is the evaporator/condenser itself. The vapor generated in the evaporator flowed upward and condensed in the condenser which then returned the condensate to the evaporator via gravity.

B. AUXILIARY EQUIPMENT

1. 8 Ton Refrigeration Unit

This unit was used to cool the ethylene glycol/water mixture (coolant) to the desired temperature needed to condense the refrigerant vapor. For the present pool boiling experiments, the temperature control was set to maintain the sump at 5°C. This

refrigeration unit had a cooling capacity of 28 kW (8 tons) with a 30 gpm pump providing circulation of the coolant to achieve the set temperature. To prevent damage of the unit, several safety features were provided: low temperature cutout, high pressure cutout, low flow cutout, and a hot gas bypass which allowed for continuous operation. For operation procedures, see Appendix E.

2. Ethylene Glycol/Water Mixture

The coolant used was a 54% by weight ethylene glycol/water mixture. This was used to control the system pressure by circulating it through the condenser.

3. Pumps

There were two pumps available to circulate the coolant from the sump through the condenser. Pump number one fed four test tubes and one of the secondary condenser coils. Pump number two was used to feed the other four secondary condenser coils. Pump number one provided enough cooling for tests up to five evaporator tubes. However, during bundle and simulation evaporator operation, both pumps were needed at heat fluxes above approximately 60,000 W/m^2.

4. Flowmeters

Four calibrated float-type flowmeters, connected to pump number one, were used to measure the flowrate passing through the four test condenser tubes. One additional flowmeter which was connected to pump number two was used to measure the total flow to the secondary condenser coils. In addition, each of the four secondary condenser coils had a globe valve to further regulate (or shut off) flow as desired. In the test tubes, the flow was regulated by a ball valve.

C. DATA ACQUISITION SYSTEM/INSTRUMENTATION

As described by Akcasayar [Ref. 8], a Hewlett Packard HP-3497A Data Acquisition System, HP-9125 computer and HP-701 printer were used for data acquisition, data

reduction and data printing respectively. Although an HP-9826 computer and HP-7470A plotter can be used for final graph printing, a Macintosh Classic computer using CricketGraph 1.3.2 was utilized. HP Basic 3.01 was used for data reduction. At the beginning of every set of runs, the HP-9125 computer had to be initialized by using three system discs if the system was turned off. As described by Anderson [Ref. 7], type-T copper-constantan thermocouple measurements (mvolts) were made on the HP-3497A with the relay multiplexer assembly equipped with thermocouple compensation. A 20 channel relay multiplexer card was used to measure the voltage output from voltage and amperage sensors. Voltage measurements were taken from separate sensors that measured the voltage going to the tube bundle, simulation and auxiliary heaters. The total amperage going through the auxiliary and simulation heaters was measured using an American Aerospace Control (AAC) current sensor. The currents of each instrumented tube heater were measured using five identical current sensors. The voltage supplied to the other active tubes was also measured but the current of each active tube was not (the total current for a pair of active tubes was measured). This was felt to be sufficient since these tubes each had the same power output (1000 W) as the test tube heaters and there was no apparent reason to monitor each active tube heat flux individually.

Computer channel assignments for data acquisition and array assignments are given in Table 1.

D. EVAPORATOR/CONDENSER

An overall view of the evaporator/condenser is shown in Figure 2. The evaporator was designed to simulate a small portion of a refrigerant flooded evaporator. Front and side views of the evaporator are shown in Figures 3 and 4. It was fabricated from stainless steel plate and formed into a short cylinder 610 mm in diameter and 241 mm long. Electrically heated tubes were cantilever-mounted from the back wall of the evaporator to

permit viewing along the axis of the tubes through the lower of two glass/Plexiglass windows mounted in the front. The glass was used on the refrigerant side in order to prevent crazing or cracking of the Plexiglass and the Plexiglass gave the glass added strength. Figure 5 is a schematic sectional view of the evaporator that shows the four kinds of heated tubes used in this study. The four kinds of heater tubes were as follows: Instrumented, Active, Auxiliary, and Simulation. Table 2 gives the power rating for the heaters and the number used in the evaporator.

The electric power can be applied separately to each set of heaters using a STACO 240V, 23.5 KVA rheostat controller shown in Figure 6. Also, the desired number of instrumented tubes, active tubes, auxiliary, or simulation heaters can be turned on by using individual circuit breakers. The four auxiliary heaters, each with a maximum rating of 4 kW, were installed two on each side of the test bundle to maintain the liquid pool at saturated conditions and to provide system pressure control. The five simulation heaters, also capable of 4 kW each, were mounted below the test bundle in order to simulate additional tube rows in a larger bundle and to provide inlet vapor quality into the bottom of the test bundle as suggested by Webb [Ref. 17]. The auxiliary and simulation heaters had to be used with caution to avoid breakdown of the refrigerant.

The tube bundle consists of instrumented, active, and dummy tubes. The location of each tube is represented by the respective letter I, A, and D shown in Figure 5. The test bundle consisted of two types of heated tubes: active tubes (marked "A") which contained 1 kW cartridge heaters, and instrumented tubes (marked"I") which, in addition to the 1 kW cartridge heaters, contained six wall thermocouples. In measuring boiling heat-transfer coefficients, great care must be exercised with the cartridge heater and temperature measuring instrumentation to ensure good accuracy. For example, the type of heater used could have an affect on heat transfer. Bergles [Ref. 19] stated that the method of heating is

immaterial except for the case of a.c. resistance heating which may cause bubble generation in phase with the power supply. However, more recently, Jung and Bergles [Ref. 20] who carried out extensive pool boiling data with R-113, concluded that the heat transfer coefficient of a single tube in pool boiling is not sensitive to variations in the cartridge heater heat flux provided that enough thermocouples are used to measure an average wall temperature. Prior to this investigation, the instrumented test tubes were fabricated in a similar way to those used by Hahne and Muller [Ref. 21] and Wanniarachchi et al. [Ref. 22]. The exact procedure can be found in Eraydin [Ref. 9]. Figure 7 is a cross-sectional sketch of an instrumented tube used during this thesis, showing the construction details and the location of the wall thermocouples. The thermocouples were imbeded in the wall at different circumferential and longitudinal positions along the heated section of the tube. The instrumented tubes were located along the centerline of the tube bundle, forming a vertical in-line column. All the instrumented and active tubes were Turbo-B tubes made by Wolverine. These tubes were 14.15 mm in diameter and were arranged in an equilateral triangular pitch (i.e. centerline-to-centerline spacing) of 19.1 mm, giving a pitch-to-diameter ratio of 1.35. The bundle also contained a number of unheated dummy smooth tubes (marked "D") that were used to guide the two-phase mixture through the bundle. The dummy tubes were made from commercially available 15.9 mm in diameter smooth copper tubing. Two vertical baffle plates were made of aluminum to restrict circulation into and out of the bundle from the sides . A small open space approximately 5 mm in height was left between the bundle and the dummy tube rack. This space allowed some liquid to enter the bundle and replace the vapor being generated in the bundle. However, there was also a space below the dummy rack that provided the majority of the circulation. Thus, liquid/vapor circulation was vertically upward over the five instrumented test tubes with no net horizontal component. The dummy rack (Figure 8) used 12 tubes made of solid

aluminum rods each 15.9 mm in diameter and spaced 19 mm from centerline to centerline. This rack had a triangular pitch arrangement with vapor retaining plates on the side and was used for two purposes. This dummy rack was designed to collect all rising two-phase flow generated by the simulation heaters and direct it to the test section. The other purpose was to simulate the vapor passing though a larger bundle before reaching the instrumented tubes. The liquid-vapor mixture after passing through the bundle was separated when it reached the pool surface. The vapor flowed toward the condenser and the liquid was circulated back toward the bottom of the bundle.

The condenser included four test tubes (each 2 m in length) in a vertical in-line column and five auxiliary copper coils used to regulate the pressure in the system. It was designed to permit independent condensation studies of small in-line tube bundles, using the evaporator as a source of vapor. All these tubes and coils were cooled by a refrigerated mixture of water and ethylene glycol. Each of the test tubes and auxiliary coils could be operated separately using ball or globe valves respectively to regulate the desired flow rate. The vapor that was produced in the evaporator was guided up toward the top of the condenser by a vapor shroud as shown in Figure 9. The vapor was then directed down over the condenser tubes and coils where it condensed. Once condensed, the force of gravity returned the condensate back to the evaporator. Observation windows in both the condenser and the evaporator allowed for easy viewing of condensation and boiling.

E. GEOMETRY OF ENHANCED SURFACE USED

1. Turbo-B Tube

The Turbo-B tube, manufactured by Wolverine Tube Inc., has a enhanced surface geometry. The exterior boiling enhancement is made by raising integral low fins, cutting diagonally across these fins, and then rolling the fins to compress them to form mushroom-like pedestals [Ref. 23]. This process forms numerous re-entraint

passageways. Figure 10 shows the surface of the tube at 25 times its actual size. The tube is currently available in copper, cupro-nickel, and low carbon steel. The relative dimensions of the tube used in the present experiments are:

Tube material - Copper

Outside diameter = 14.15 mm

Inside diameter = 12.7 mm

Enhanced surface length = 203.2 mm

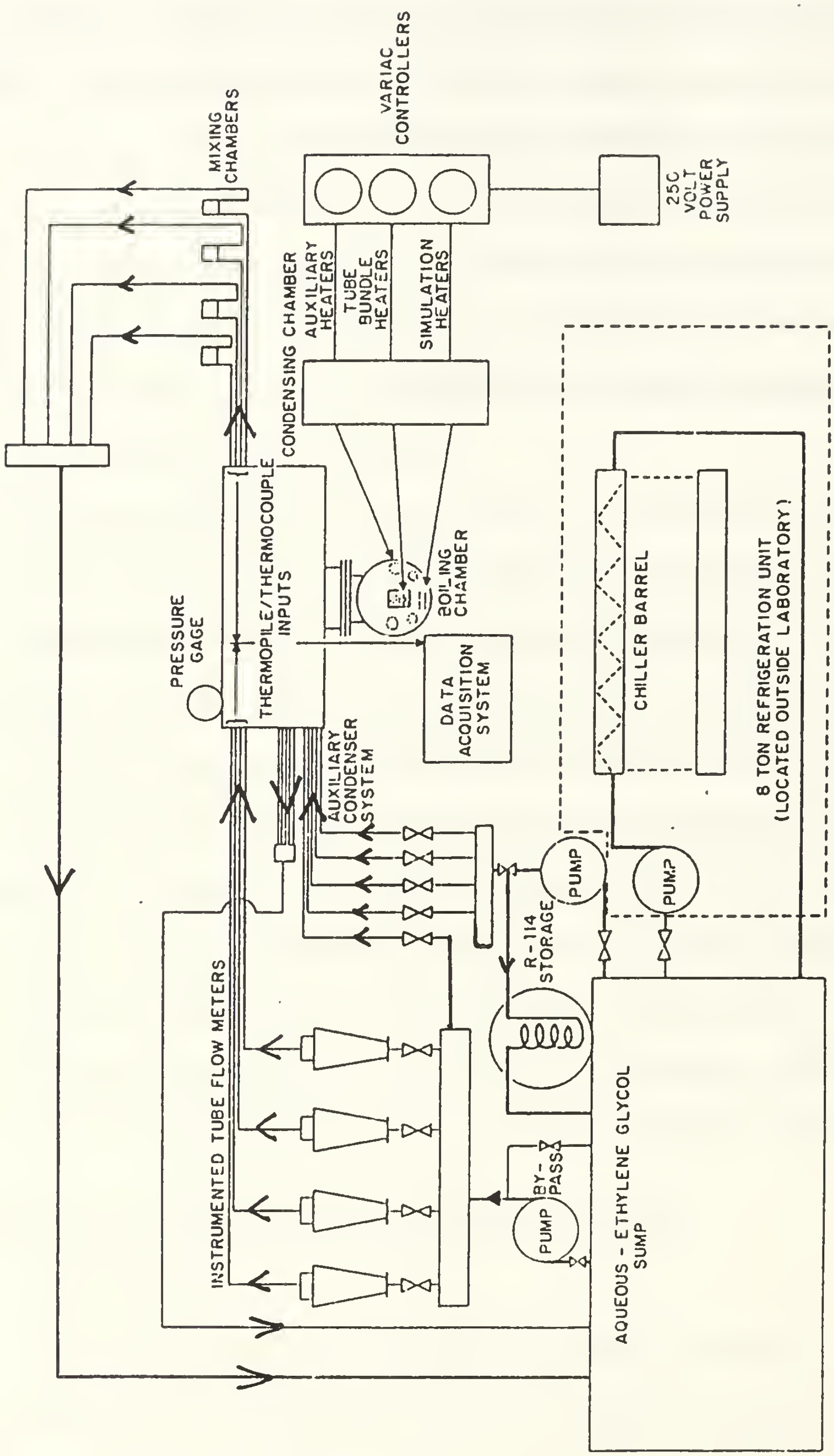

Figure 1. Schematic View of the Apparatus

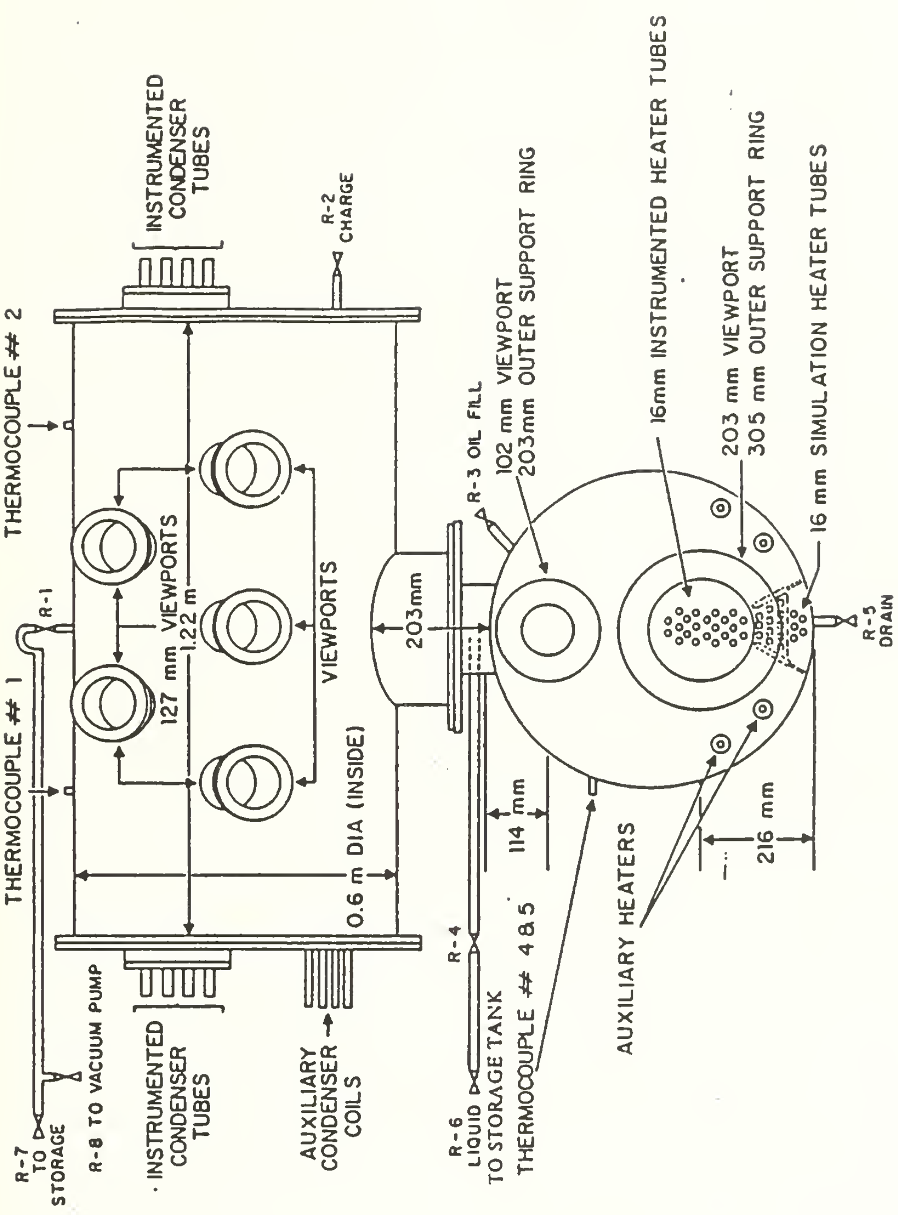

Figure 2. Evaporator/Condenser Schematic

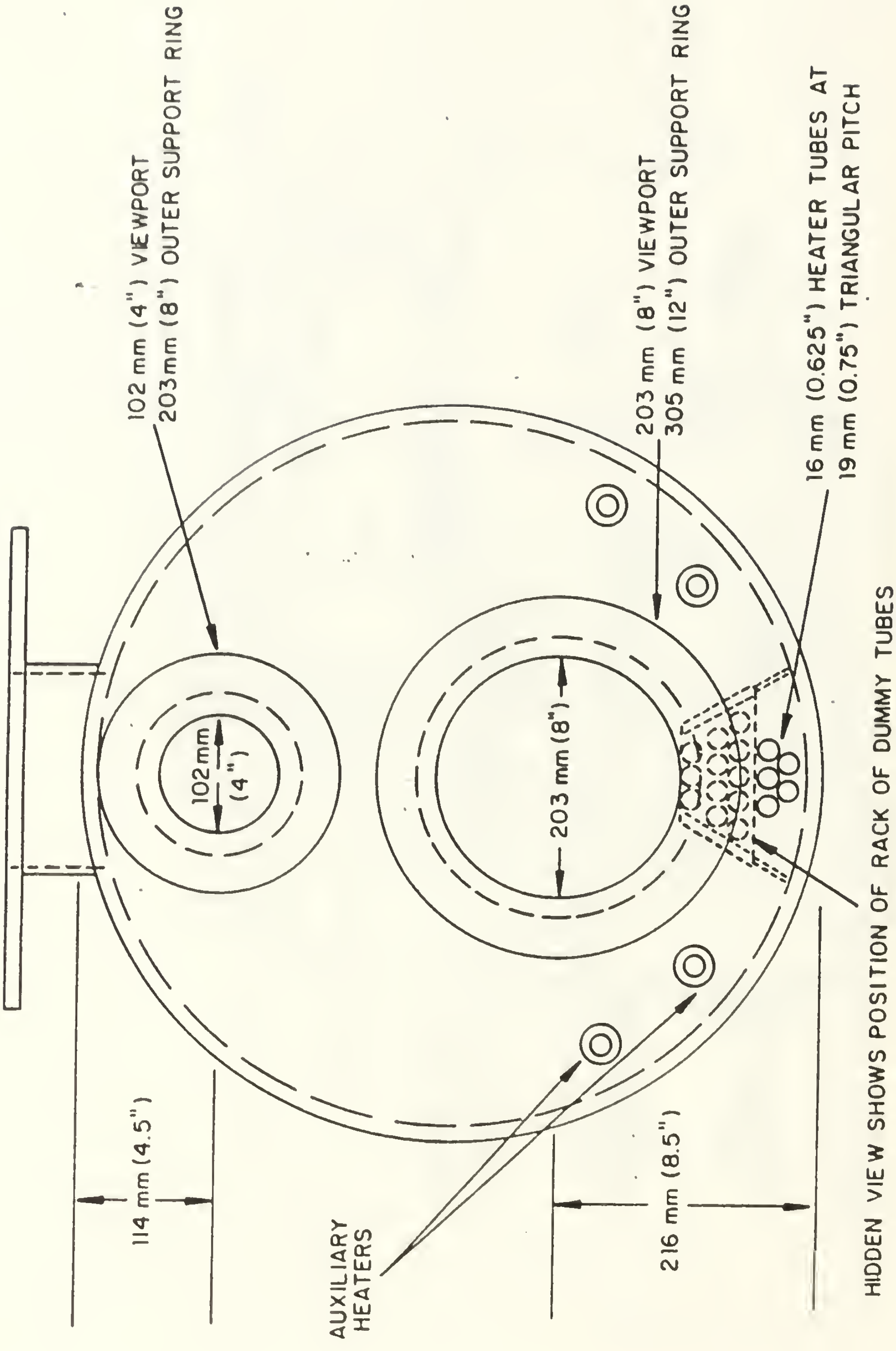

Figure 3. Front View of Evaporator

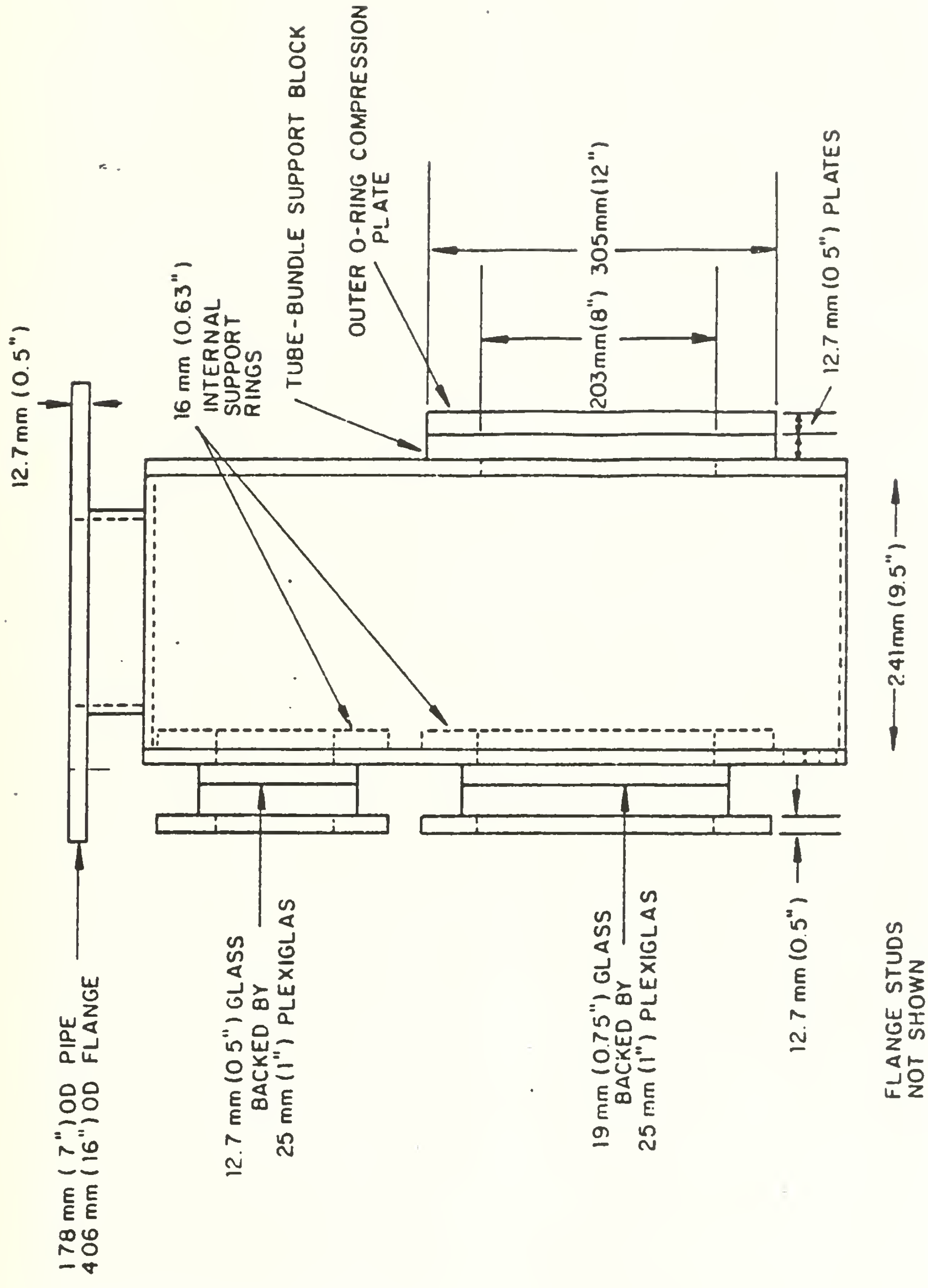

Figure 4. Side View of Evaporator

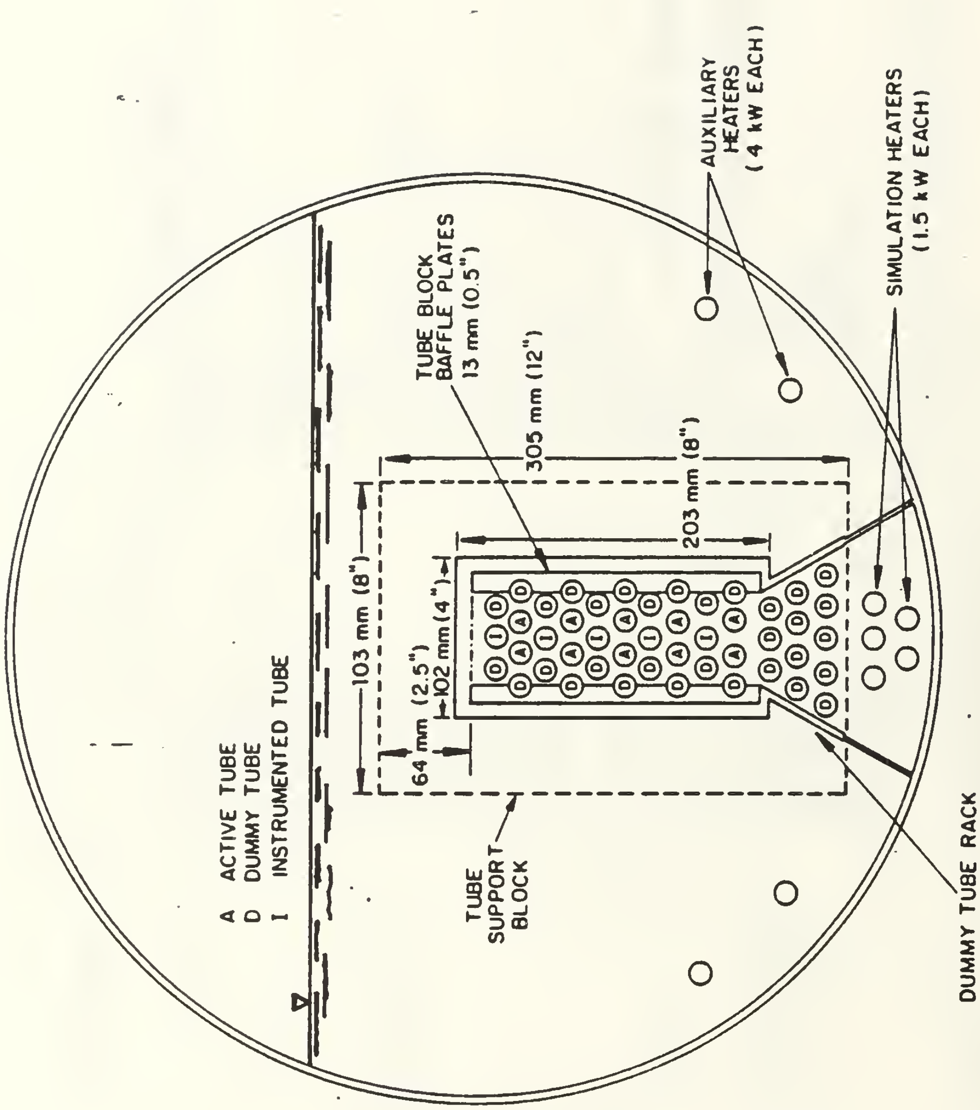

Figure 5. Sectional View of Evaporator Showing Tube Bundle

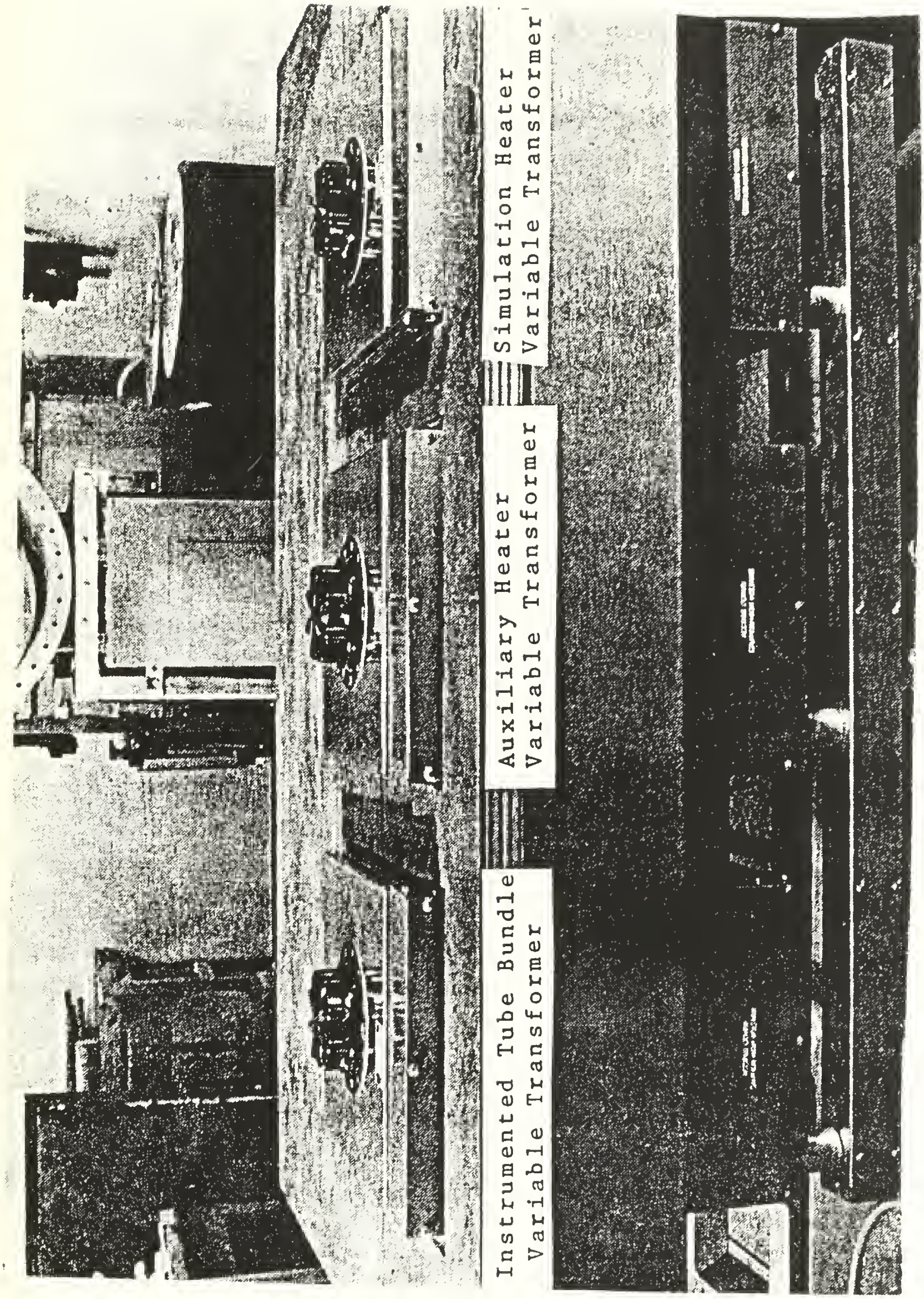

Figure 6. Photograph of 208 V, 75 A, Variable Transformers

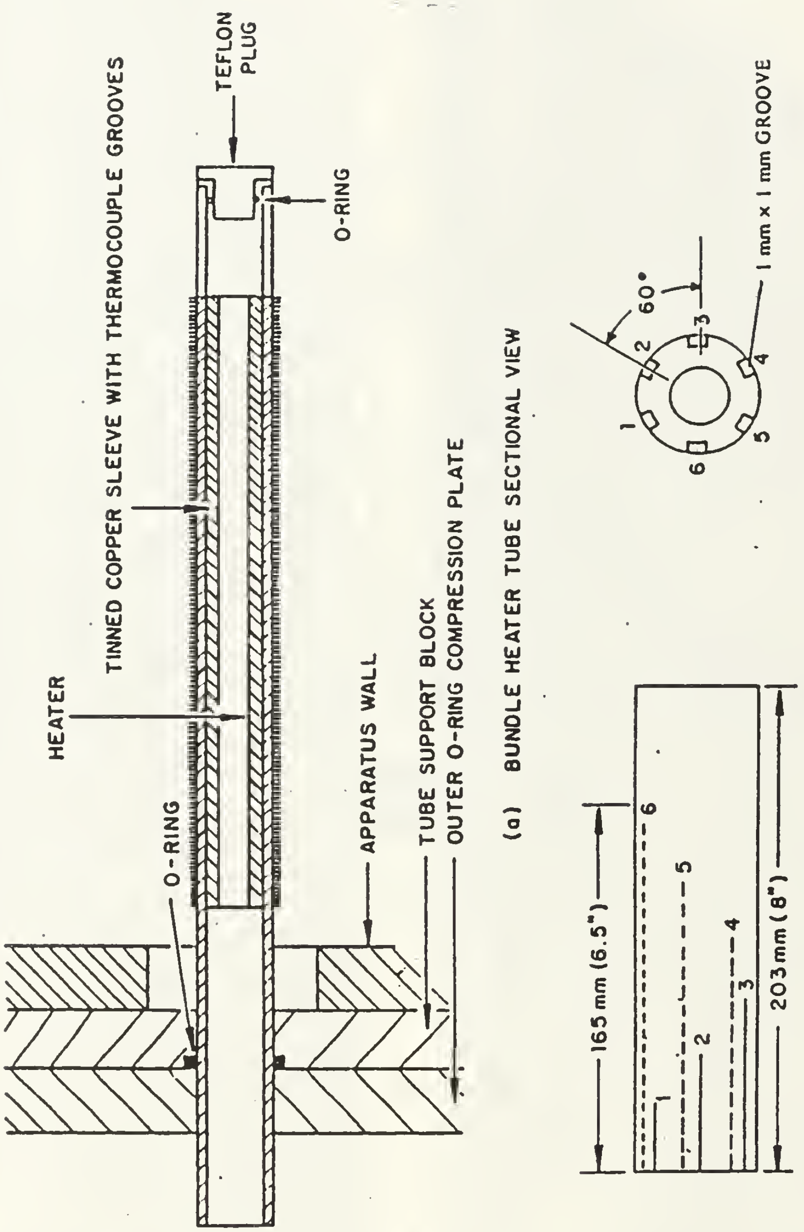

Figure 7. Thermocouple Locations on an Instrumented Boiling Tube and Tube Section View.

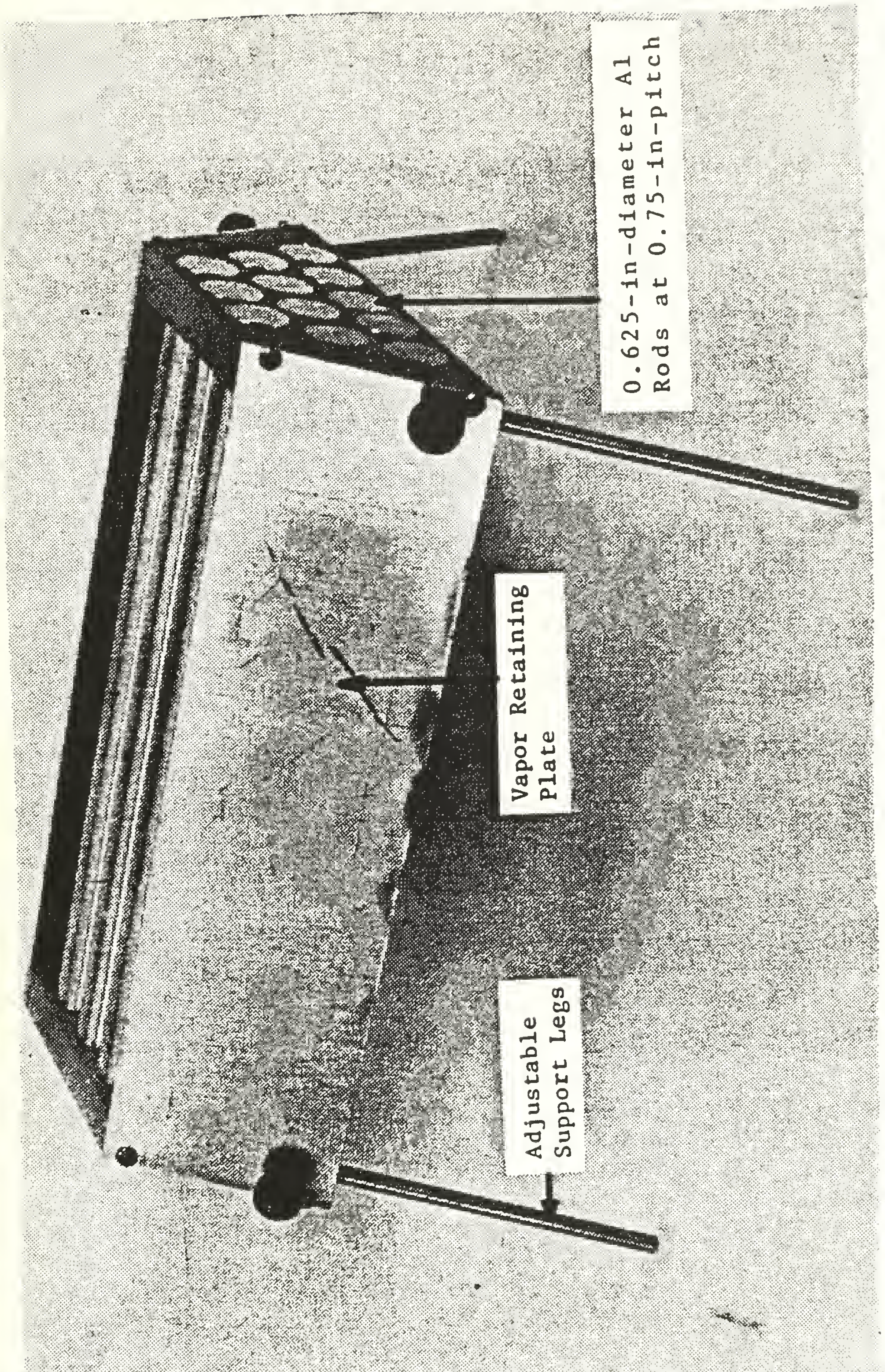

Figure 8. Photograph of Dummy Tube Rack

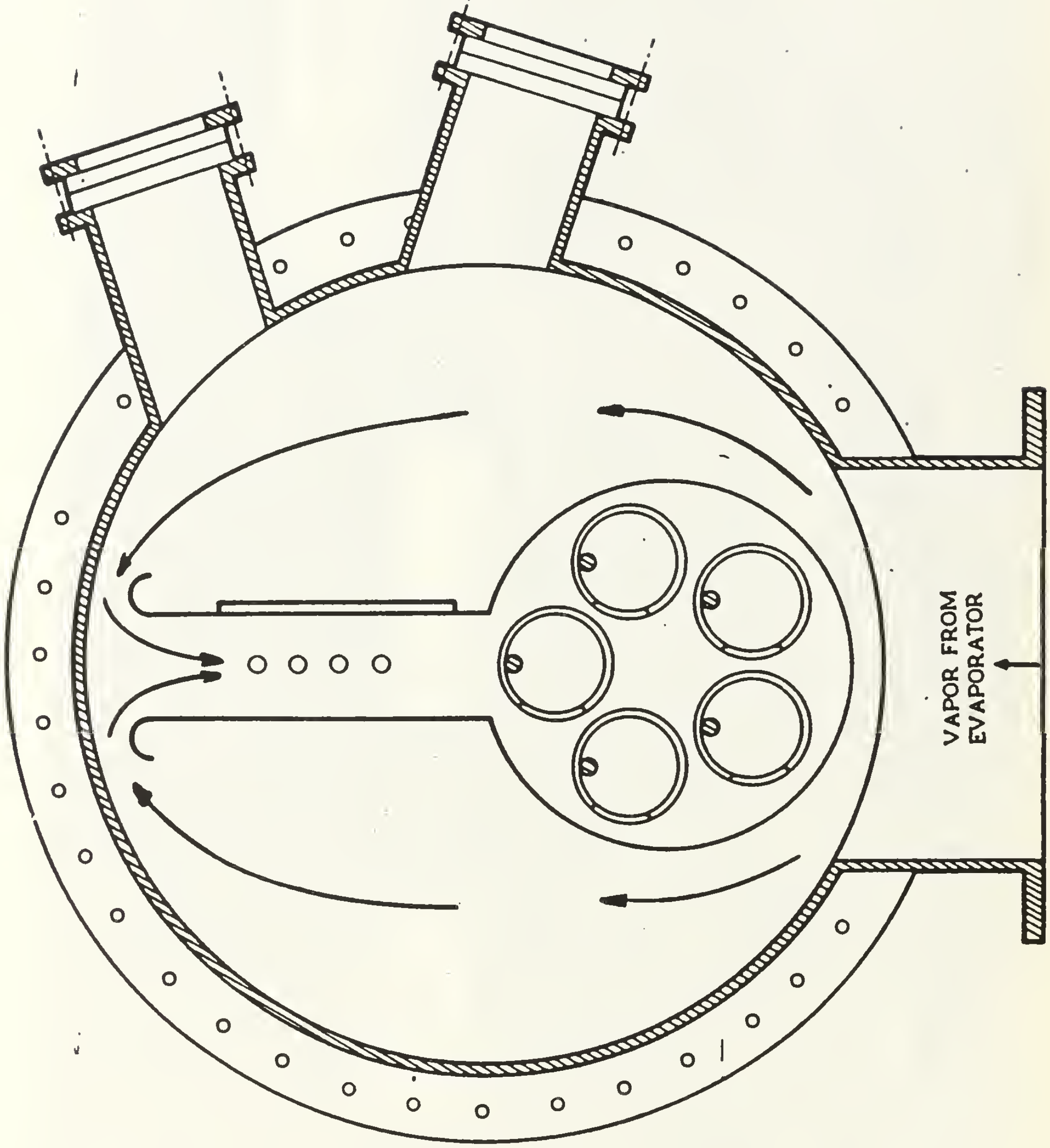

Figure 9. Vapor flow path in Condenser

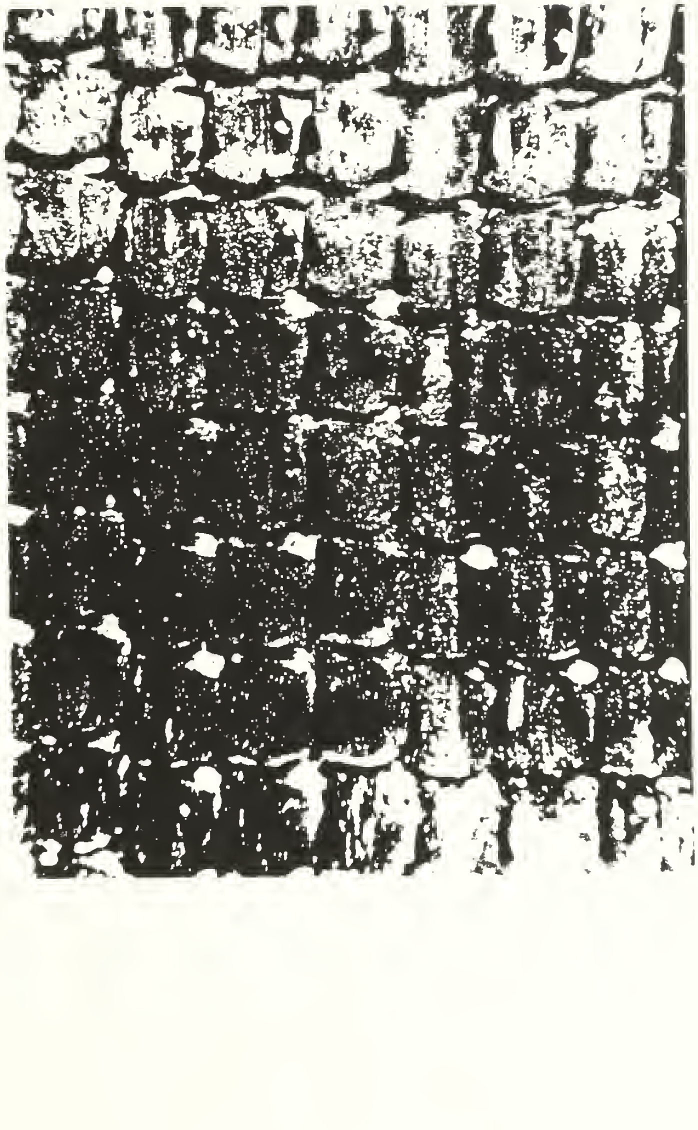

Figure 10. Close-up View of Turbo-B Tube Surface (25 Times)

TABLE 1. COMPUTER/DATA ACQUISITION ASSIGNMENT

Thermocouple Description	Channel	Array in code
Vapor 1-Top of Condenser	00	T(0)
Vapor 2-Top of Condenser	01	T(1)
Vapor 3-Top of Evaporator	02	T(2)
Liquid 1-Top of bundle	03	T(3)
Liquid 2-Top of bundle	04	T(4)
Liquid 3-Bottom of bundle	05	T(5)
Tube 1,No. 1	40	T(6)
Tube 1,No. 2	41	T(7)
Tube 1,No. 3	42	T(8)
Tube 1,No. 4	43	T(9)
Tube 1,No. 5	44	T(10)
Tube 1,No. 6	45	T(11)
Tube 2,No. 1	46	T(12)
Tube 2,No. 2	47	T(13)
Tube 2,No. 3	48	T(14)
Tube 2,No. 4	49	T(15)
Tube 2,No. 5	50	T(16)
Tube 2,No. 6	51	T(17)
Tube 3,No. 1	52	T(18)
Tube 3,No. 2	53	T(19)
Tube 3,No. 3	54	T(20)
Tube 3,No. 4	55	T(21)
Tube 3,No. 5	56	T(22)
Tube 3,No. 6	57	T(23)
Tube 4,No. 1	58	T(24)
Tube 4,No. 2	59	T(25)
Tube 4,No. 3	60	T(26)
Tube 4,No. 4	61	T(27)
Tube 4,No. 5	62	T(28)
Tube 4,No. 6	63	T(29)
Tube 5,No. 1	64	T(30)
Tube 5,No. 2	65	T(31)
Tube 5,No. 3	66	T(32)
Tube 5,No. 4	67	T(33)
Tube 5,No. 5	68	T(34)
Tube 5,No. 6	69	T(35)

TABLE 1. COMPUTER/DATA ACQUISITION ASSIGNMENT (CONT.)

Amperage Sensor Description	Channel	Array
Tube 1	30	Amp(0)
Tube 2	31	Amp(1)
Tube 3	32	Amp(2)
Tube 4	33	Amp(3)
Tube 5	34	Amp(4)
Active Heater Group 1	35	Amp(5)
Active Heater Group 2	36	Amp(6)
Active Heater Group 3	37	Amp(7)
Active Heater Group 4	38	Amp(8)
Active Heater Group 5	39	Amp(9)
Auxiliary Heaters	25	Amp(10)
Simulation Heaters	26	Amp(11)

Voltage Sensor Description	Channel	Array
Instrumented/Active	27	Volt(0)
Simulation Heaters	28	Volt(1)
Auxiliary Heaters	29	Volt(2)

TABLE 2. EVAPORATOR HEATERS

Heater Type	Number	Power Rating per Heater
Instrumented Tube Heaters	5	1000W
Active Tube Heaters	12	1000W
Auxiliary Heaters	4	4000W
Simulation Heaters	5	4000W

IV. EXPERIMENTAL PROCEDURES

A. REMOVAL OF TUBE BUNDLE FROM EVAPORATOR

Before removing the tube bundle from the evaporator, it was ensured that the evaporator was free of any refrigerant and was at atmospheric pressure. The tube bundle support block bolts were then loosened and removed. The tube bundle was then removed from the back of the boiler. Care was taken when removing the tube bundle as to not damage the thermocouple or heater wires. It was easier to disconnect the thermocouple wires from the data acquisition board and the heater wires from the power panel instead of leaving them connected to the tubes when it was necessary to work on or clean the tubes in the bundle. The tube bundle consisted of five instrumented heated Turbo-B tubes, 10 active heated Turbo-B tubes, 18 dummy smooth tubes and two dummy Turbo-B tubes. These two dummy Turbo-B tubes were equipped with heaters and could be connected if desired to study various other bundle configurations (see Anderson [Ref. 7]).

B. BUNDLE DISASSEMBLY

When the bundle needed to be disassembled, it was ensured that there was a clean working space and a container to put small parts in during the procedure. The first process was to remove the perspex plate attached to the aluminum baffle plate by four screws. This plate was modified such that the eight dummy smooth tubes surrounding the instrumented tubes extended through the plate (with ptfe plugs which held the tubes in the proper pitch-to-diameter alignment). This alteration became necessary since at high heat fluxes, the smooth tubes (which were screwed into the tube support block) loosened from the wall and rattled around. The ten screws on each aluminum baffle plate were then removed. The plates were then pulled off the bundle. The two outside smooth dummy tubes remained on

the tube bundle support block as they were countersunk into the block. The three inner smooth tubes could be removed from the aluminum block as they were attached only by the screws already removed. The 12 smooth tubes were then unscrewed from the tube bundle support block as seen in Figure 11. Care was taken in noting the order in which all the tubes were removed as it saved time in reassembly. The bundle was engraved to help in this process. With these tubes and baffle plates removed, only the instrumented and active heater tubes remained. These tubes were removed by loosening the outer O-ring compression plate; this allowed the tubes to be pulled from the tube support block. Care was taken when pulling the tube from the tube support block so as to not break the thermocouple or heater wires.

C. SYSTEM CLEAN-UP

If the system was contaminated it had to be thoroughly cleaned. In order to do this, the entire apparatus had to be taken completely apart and cleaned in the following manner.

After removal of the R-113 from the evaporator and system at atmospheric pressure, all electrical connections to the bundle were disconnected and the front-viewing glass windows were removed. The tube bundle was then be removed as described above. The dummy tube rack was then taken out; at all times, the system was ventilated with a fan.

Having removed the tubes from the tube bundle, they were individually washed with warm water, rinsed and then wiped down with acetone. The smooth tubes were cleaned with Copper Brite to remove any tarnish. They were wiped down with warm water and acetone. The same procedure was followed for the Turbo-B tubes except they were not cleaned with Copper Brite. During the cleaning process, a soft bristled toothbrush was used to ensure the enhanced surface was cleaned properly, exercising care not to interfere with the tube surface. The storage tank, if thought to be contaminated also was drained, vented, opened and cleaned using the same procedure.

D. SYSTEM REFIT

1. Installation of tube bundle in evaporator

Prior to installing the evaporator tubes and support block, the bundle and evaporator was thoroughly wiped down with acetone. Once the evaporator tubes were installed in the support block, and prior to tightening the tube bundle support block nuts, the bundle was guided into the evaporator section. After the bundle was in position, it was then checked that the dummy rack was still properly positioned below the bundle and that the vapor thermocouple positions were still 1.75 cm above the bundle. The support block nuts were then tightened equally on opposite sides to give equal compression of the gasket. If the front window was removed during maintenance, the window was put back on very carefully with small equal torques applied to each nut, in turn, in a clockwise direction around the outer ring support. After the window was in place, each tube (which extended through the outer O-ring compression plate) was tapped forward so as to touch the front-viewing-window. Once completed, the O-ring compression plate was tightened. This compressed the O-rings (which were slightly undersized because the tubes were so close together) providing a seal between the tube support block and the stainless-steel backing plate. Also, the compression plate had grooves for the O-rings to fit into to ensure proper alignment and seal.

2. System Leakage Check

After the system was isolated from the atmosphere and system integrity restored, a Seargent Welch 10 SCFM vacuum pump was turned on and the pressure in the system was reduced to 25 in-Hg vacuum. The system was then secured and left untouched for at least 10 hours to see if there was any leakage. If there was significant leakage(>1 inHg), then the system vacuum was broken by cracking valve R-2 (Figure 2) slowly (to ensure minimum moisture was allowed to enter the system). This valve was left open until

the system was at atmospheric conditions. The system was then pressurized with air to approximately 5 psig through valve R-2. Large leaks were then detected by simply listening to the air issuing from the system. If the leaks were small, they could be found by applying a small amount of soap/water solution to all joints in the system. One leak that was found was where the sleeve had been soldered onto the Turbo-B tube. Since this was found to be the source of a leak, all the Turbo-B tube joints were carefully resoldered. After all leaks had been corrected, the system was again subjected to a vacuum for a minimum of 10 hours. If the increase was less than 1/2 to 1 inHg rise in a 10 hour period, then the system was filled with refrigerant.

E. REFRIGERANT

1. Fill

a. From System Storage Tank

A refrigerant storage tank was used to store excess R-113 during experiments. The storage tank prevented discharge of the R-113 into the atmosphere and made experimentation less costly. To fill the evaporator with R-113 from the storage tank, the system pressure was equalized to the storage container pressure by opening valves R-1 and R-7 (Figure 2). Once the pressure was equal, then valves R-6 and R-4 were opened. Due to the pressure difference caused by the hydrostatic head of the liquid in the storage container, R-113 flowed from the storage tank into the evaporator. The amount of refrigerant that was transferred was controlled by throttling valve R-4 to obtain the desired level. Once the desired amount of refrigerant had been transferred, valves R-4, R-6, R-7, R-8 were closed. If required, additional R-113 was later added from a storage drum at atmospheric pressure to the system using valve R-2 (see next section).

b. From Refrigerant Storage Canister

To fill the apparatus from the refrigerant drum, the ethylene glycol/water mixture was first cooled to a temperature of 5°C. Both condenser pumps were put into operation thus allowing coolant to flow through the condenser section. This allowed for a differential pressure to exist between the evaporator and ambient. A clean plastic hose was connected to valve R-2 (Figure 2) and the other end was end put in the refrigerant drum. Once this differential pressure and hose hookup was completed, refrigerant transfer between ambient and the evaporator was possible by slowly opening valve R-2.

2. Removal

a. To System Storage Tank

For tube replacement, system maintenance or clean-up purposes, the R-113 was transferred to the storage tank. The ethylene glycol/water mixture temperature flowing through the storage tank was cooled to less than 5°C; valves R-7 and R-8 (Figure 2) were opened and the vacuum pump was turned on to put the storage tank under vacuum. Once the storage tank was under a vacuum, R-113 flowed from the evaporator to the storage tank because of the pressure difference. This pressure difference was maintained by keeping the heaters on in the evaporator and the coolant flow through the storage tank. As the level in the evaporator came down, power to the heaters was secured to avoid overheating. Any remaining R-113 that could not be transferred into the storage tank was drained through valve R-5 and put into a drum to be used later.

b. To Refrigerant Storage Canister

This procedure is primarily used to change refrigerants. The system vacuum can be broken by slowly cracking open R-2 (Figure 2) to ensure that moisture was not allowed to enter the system. Once the system was at atmospheric pressure, valve R-2

was opened wide to allow air to enter when the refrigerant was removed. The refrigerant could then be drained through valve R-5 and put into a drum to be used later.

F. OPERATION

1. System Lightoff, Securing and Emergency Procedures

See Appendix E

2. Normal Operation

The evaporator was filled with R-113 to a level of approximately 10 cm above the top tubes in the bundle. Prior to operating the system, the 8-ton refrigeration unit was run for approximately an hour to reduce the ethylene-glycol/water mixture in the sump to a temperature of 5°C. The pressure in the evaporator was usually 14 to 16 inHg vacuum if the system was left secured overnight. As the sump was brought to temperature, the data acquisition system and computer were turned on. This allowed the temperature in the system to be monitored during warm-up to saturation conditions. With this and pump number one running, the auxiliary heaters were then used to bring the pool up to saturation temperature. The auxiliary heaters were set to 1 kW nominal after pool temperature had been reached. The system pressure was slowly raised by allowing minimal coolant to flow at a low rate through the condenser tubes while heating the system with the auxiliary heaters. Once the required saturation temperature of 47.5°C was reached, the instrumented tubes were switched on and set to the desired value. This was done to prevent the tubes from nucleating prematurely. The heat flux of the instrumented tubes was then slowly increased by adjusting the rheostat. For increasing heat flux, the data were taken with very small heat flux increments, waiting at least 5 minutes to attain steady state conditions at each heat flux. At all regions of the boiling curve (and especially near the onset of nucleate boiling), two readings were taken for each heat flux. The bundle was continuously monitored through the observation windows.

Figure 12 shows the tube bundle arrangements used during experimentation. Test One was with only instrumented tube number one on in the bundle. Test two was with instrumented tubes one and two on in the bundle. Test three was with instrumented tubes one, two and three on in the bundle. Test four was with instrumented tubes one through four on in the bundle. Test five was with all five instrumented tubes on in the bundle. Test six was all five instrumented tubes plus all five pairs of active heater tubes on in the bundle. Test seven was the same as test six but with the simulation heaters on.

G. DATA REDUCTION PROCEDURES

The data reduction program "DRP4A" was used during the experiments for processing the data collected. The program was written in HP Basic 3.01 and run on an HP-9000 series computer. The characteristics and capabilities of this software and the entire listing of the program is similar to that provided by Anderson [Ref. 7]. The following modifications were made:

1. Correction for pool height

2. Installation of new thermocouple at bottom of liquid pool (bundle inlet temperature)

The entire program is included in Appendix F to provide continuity for future thesis work.

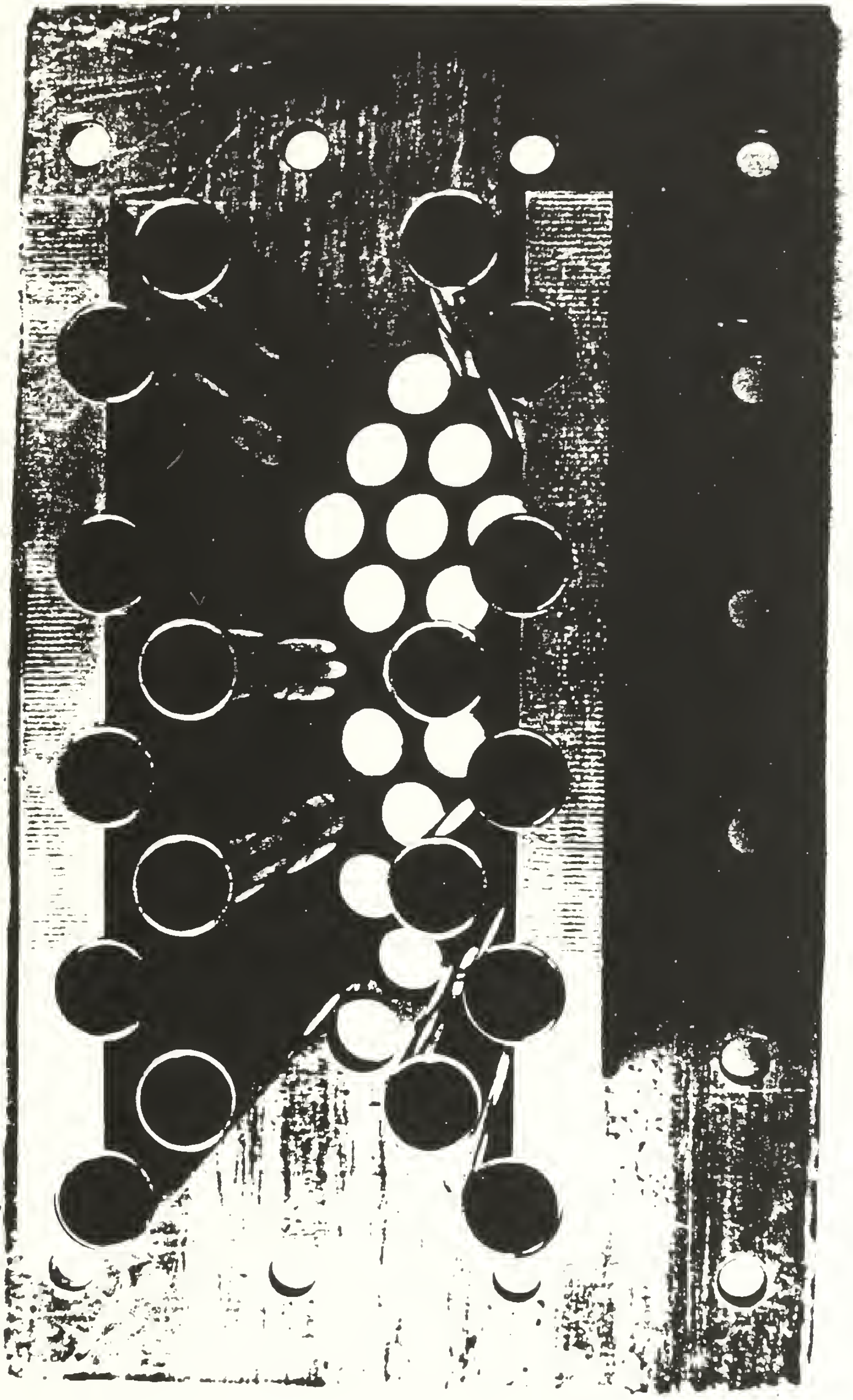

Figure 11. Photograph of Tube Bundle Support Block

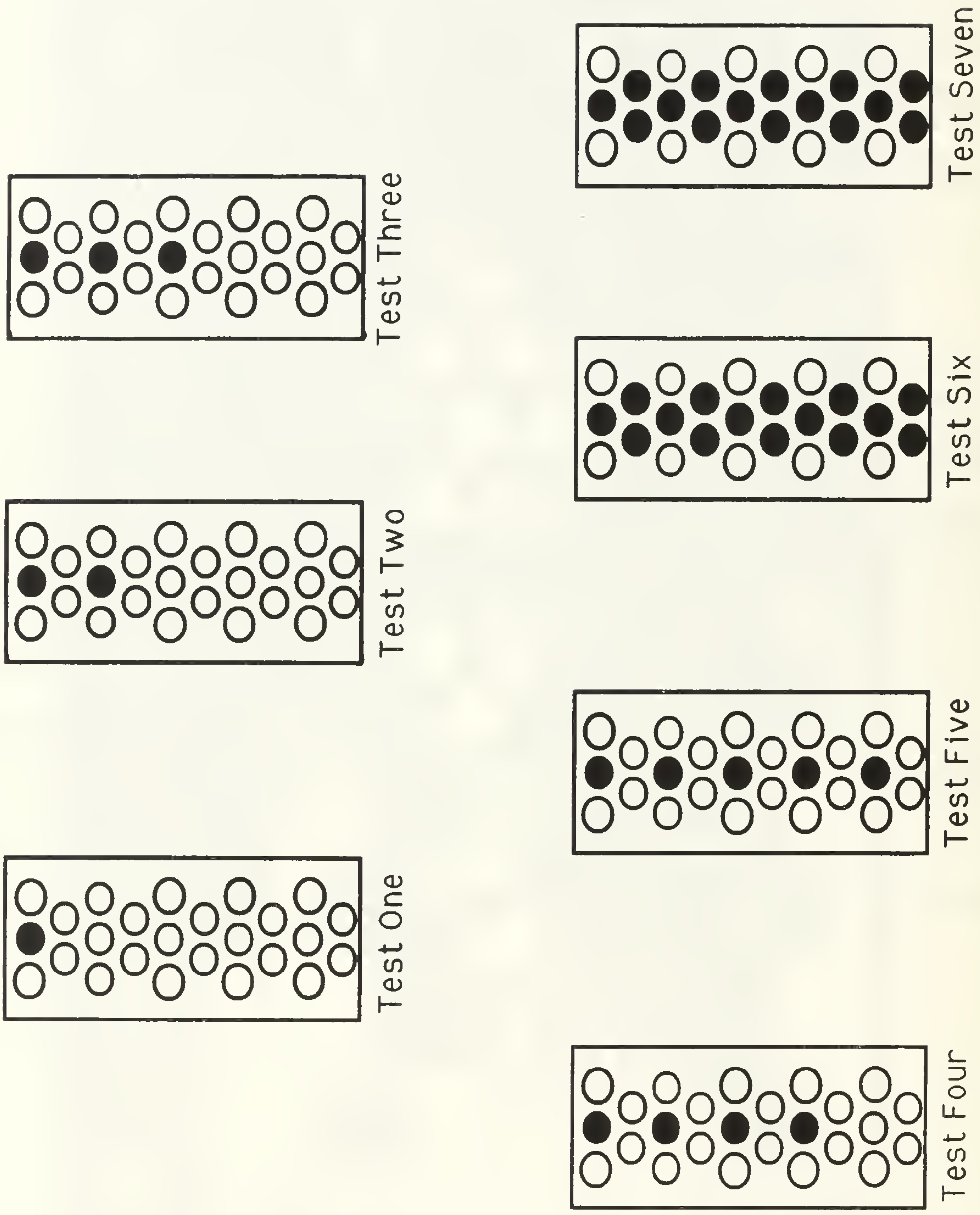

Figure 12. Tube Bundle Arrangements used During Experimentation

V. RESULTS AND DISCUSSION

A. GENERAL COMMENTS

The results are presented in five sections with sub-sections as appropriate. The first section discusses the natural convection, nucleate pool boiling phenomena and hysteresis effects within a small enhanced tube bundle. The second section discusses how evaporator pool height above the tube bundle affects the nucleation site activation and general evaporator performance. The third section looks at the effects of auxiliary heaters. The fourth section discusses the effect of surface history on nucleation site activation/deactivation. The final section shows comparisons of data taken during this thesis with previously obtained data at the Naval Postgraduate School.

A list of data runs conducted during this investigation may be found in Appendix A. All data files used in this thesis use the following filename sequence. Each file is composed of five sets of alpha-numeric characters used to describe the experiment.

First set (1 char.)	Heat flux	I(Increasing heat flux) D(Decreasing heat flux)
Second set (2 char.)	Type of tube used	TB (Turbo-B)
Third set (2 char.)	Number of Experiment for accounting purposes	

To give an example, the file name ITB12 means "increasing heat flux, using a Turbo-B tube and the 12th data run. If more detail is desired about a data run, see Appendix A. All plot files are similar to data files except they start with the letter "P". All tests were done with the auxiliary heaters at either 0, 1, or 3 kW nominal power setting (for details see Appendix A).

All the graphs show heat flux (W/m^2) along the ordinate (y axis) and wall superheat (K) along the abscissa (x axis). The heat flux was changed through the use of a variac from 600 to 100,000 W/m^2 for increasing or 100,000 to 600 W/m^2 for decreasing runs. Approximately 25-30 points were taken on the increasing heat flux and about 20 points were taken for the decreasing heat flux. The wall superheat is the difference between the corrected average tube wall temperature and the liquid saturation temperature.

To clarify the operation of the evaporator during the above tests, we used seven basic bundle arrangements during the test procedures as discussed and shown in Chapter IV.

Anderson [Ref. 7] used four types of surface preparation techniques.

1. Surface preparation A maintains the evaporator tube(s) at a heat flux of 30 kW/m^2 for one hour, slowly reducing heat flux to a minimum value of around 1 kW/m^2, and beginning data collection immediately at successively increasing heat fluxes. The motivation for this surface preparation is a widely varying dynamic load often encountered in an air-conditioning machine.

2. Surface preparation B simulates an operating refrigeration system undergoing frequent off-cycles. A heat flux of 30 kW/m^2 at saturation conditions is maintained for one hour. Power is then secured for 30 minutes and then data are taken at successively increasing heat flux steps.

3. Surface preparation C represents the initial start-up of a refrigeration system. During this process, the evaporator was brought up to temperature and pressure with the auxiliary heaters alone to ensure the tubes did not have any active nucleation sites. Once at saturation pressure, the tube was turned on and the heat flux varied from 600 to 100,000 W/m^2 to develop a heat flux versus wall superheat plot. This process is very interesting as it introduces many complexities such as boiling hysteresis.

4. Surface preparation D represents a continuous operating air-conditioning system. It is closely modelled by a continuously decreasing heat flux starting from maximum power of 100 kW/m^2 after it has been boiled at this power for one-half hour. Considering that the return flow to the boiler is normally two-phase, nucleation sites are maintained active throughout the evaporator tube bundle. The decreasing heat flux data runs are normally the most readily reproducible and are used most often in measurements of tube-bundle performance. This surface preparation is the most widely used for reporting the performance of evaporator-tube surfaces.

Three of these surface preparation techniques were used during the course of the present work. Surface preparation technique C and D were used exactly as stated above and surface preparation technique B was the same but with a modification. Surface preparation technique B was modified such that power to the tube heaters could be secured for any amount of time but the pool temperature had to be maintained at saturation temperature.

1. Repeatability of data

Figure 13 presents similar data taken on two different days for the top tube operating alone in the bundle; the repeatability is seen to be very good. The arrows on the figure indicate the familiar hysteresis loop. The two tests show very similar temperature overshoot values (indicated by the horizontal line). The point of incipience (point where nucleate boiling first occurs) is also very similar for both tests.

The heat-transfer coefficient, h, is often used as a measure of tube performance: it is found by dividing the heat flux by the wall superheat. From Figure 13, values of h in the nucleate boiling region range from 1540 W/m^2K at low heat flux to 13,750 W/m^2K at high heat flux. Corresponding values of h in the convection region range from 480 W/m^2K at low heat flux to 700 W/m^2K at medium heat flux. It can be seen from Figure

13 that the tube performance typically improves by a factor of five once the tube starts to nucleate. This explains the importance of ensuring a flooded evaporator operates in the nucleate boiling rather than the natural convection region.

Also shown on Figure 13 are typical uncertainty bands for the data at both high and low heat flux and wall superheat. It can be seen that the greatest uncertainty occurs at low wall superheat and heat flux; this was as expected since the values of wall superheat are of the order accuracy for the thermocouples.

Figure 14 shows the limited predictions that are available for both natural convection and nucleate pool boiling data. These correlations were formulated for single smooth tubes, but represents all that is available for enhanced surfaces and tube bundles. This indicates the urgent need for further work in this area. For the natural convection region, two correlations are shown: Churchill and Chu [Ref. 24] and Churchill and Usagi [Ref. 25] . The experimental data for a single tube within the bundle show an appreciable higher heat-transfer performance than prediction. This might be expected as the tube is an enhanced surface. However, in the convection region, one should not expect a large difference in performance between different tube surfaces as they are designed primarily for the nucleate region. Indeed, experiments by Murphy [Ref. 6] have shown that the data for enhanced surfaces falls on top of smooth tube data in the convection region. Consequently, the discrepancy seen is more likely to be due to circulation effects within the bundle.

In the nucleate boiling region, there is also a large enhancement seen in the experimental data when compared with the correlation of Stephan and Abdelsalam [Ref. 26]. However, in this region, the discrepancy can be explained due to the enhanced nature of the surface. Circulation effects are still likely to be present, but small for a single tube when compared to the large number of active nucleation sites.

B. BUNDLE TRENDS FOR A POOL HEIGHT OF 10 CM

Figure 15 shows the influence of tube two on tube one. One may expect the thermal currents from the lower tube to further enhance the upper tube. However, with this lower tube heated, the performance of tube one in the convection region did not change. More striking is the significantly poorer performance of tube two in this region for which no explanation can be found. It is interesting to note that tube two (which should behave as an isolated single tube in the convection region, i.e. feeling no effect from the tube above) is now in much better agreement with the natural convection correlations.

Also seen is that the top tube nucleates at a lower heat flux. However, once both tubes are nucleating, the agreement is very close, with the top tube having the slightly better performance. Although this slight discrepancy could be due to uncertainty in the data, it is more likely to be due to the influence of the bubbles coming from the tube below, especially when one compares it with the top tube acting alone (Figure 13).

Figure 16 shows decreasing heat flux for two tubes. Agreement is very close, with the top tube performing slightly better at high heat flux, but the opposite at low heat flux. However, as heat flux is reduced, the uncertainty in the data increases.

With three tubes in operation (Figure 17) , the trends are much the same. One point of interest is the effect on lower tubes as upper tubes start to nucleate. As tube one starts to nucleate, tubes two and three shift significantly to the left, indicating an increase in heat-transfer coefficient. However, tubes two and three remain in the convection region. Any further movement to the left by the upper tubes causes a corresponding shift to the left for the tubes below. This is probably due to increased circulation effects (i.e. as the bubbles from the upper tubes move around the evaporator, they help to agitate the thermal boundary layer around the tubes below). The shift to nucleation is strictly in order as one moves down the bundle.

For decreasing heat flux (Figure 18), there is a significant drop-off in performance for tube three, especially at a low heat flux. It may be that as one moves down the bundle, the greater pressure deactivates the nucleation sites at a faster rate.

Figures 19 to 22 show four and five tubes activated for increasing and decreasing heat flux. Similar trends to those already reported are seen; tube one nucleates first followed by two, three, etc. As each successive tube nucleates, the performance of the remaining lower tubes is improved slightly. In the nucleate region at high heat flux, tube one exhibits the best performance followed by tubes two, four, five and three. This somewhat strange order maybe due to uncertainty or the fact that tube three is only partially nucleating. At the very highest heat flux, all five tubes seem to coincide. At low heat fluxes, tube two gives the best heat transfer; it is unclear as to why this should be.

Because of the unexpected behavior of tube three at high heat flux, the positions of tubes three and five were switched to see if this behavior was a "bundle" effect or simply due to the particular tube itself. Figure 23 shows the results after switching for decreasing heat flux. New tube five (formerly tube three) now has the poorest performance, indicating that it is the tube rather than the bundle causing the earlier effect. It may be that air pockets surround the thermocouple junctions of tube five. Consequently, the tubes were kept in this position for the remainder of the tests, with the "bad" tube in the lowest position.

Figures 24 and 25 show the entire bundle activated for both increasing and decreasing heat flux while Figures 26 and 27 show the entire bundle plus simulation heaters activated for increasing and decreasing heat flux. These simulation heaters give the bottom of the bundle an inlet quality of about 20 percent, thereby simulating a real evaporator. Similar trends to those seen before are evident. The heat flux at which incipience occurs continues to decrease for all tubes, indicating the extra quality moving through the bundle helps to trigger "early" nucleation. As this simulates part of a real evaporator, this trend is

encouraging, as it is more likely to be operating in the nucleate region rather than the convection region. For the decreasing heat flux run, the heat transfer from the lower tubes has also been improved due to the increased vapor passing over them.

As already mentioned, it is difficult to make too many direct comparisons when all five tubes are independently instrumented. One of the tubes may have certain induced errors due to manufacture that another tube does not. Consequently, of perhaps more use is to look at what happens to the top tube only as successive tubes are activated below. Figure 28 does this for all seven tests (see Chapter IV: normal operation, for description of tests) for an increasing heat flux. In the natural convection region, the point of incipience occurs at increasingly lower heat fluxes as more tubes are activated. In the nucleate boiling region, the heat-transfer coefficient increases as more tubes are activated. Both the natural convection and nucleate boiling regions are well defined indicating good reliability of the data. For decreasing heat flux (Figure 29), the heat-transfer coefficient is again clearly increased as more tubes are activated below. This is more evident at low heat flux than at high heat flux.

C. BUNDLE PERFORMANCE WITH VARYING POOL HEIGHT

One of the objectives of this thesis was to see the effect of pool height on heat-transfer performance. Pool height here is defined as the height from the free liquid surface down to the top of the bundle (tube one). All experiments to date had been carried out at a pool height of 10 cm. Two additional heights of 0 cm and 20 cm were also studied with the same vapor pressure within the evaporator (i.e. to see the effect of pressure head on the tubes in the bundle). It is understood that a true flooded evaporator has zero pool height (indeed the top tubes operate in the bubbly froth).

Figures 30 to 42 show the same seven tests for a pool height of 20 cm as previously shown for 10 cm. The trends of all these graphs are exactly the same as for 10 cm. The

effect of the greater pool height is generally to delay the point of incipience. Figures 43 and 44 show tube one only for all seven tests (i.e. to see the effect of successive activated tubes below) for increasing and decreasing heat flux respectively. This to shows similar trends to before, with the effect of successive tubes triggering earlier nucleation on the top tube as well as enhancing the nucleate boiling heat-transfer coefficient.

Figures 45 to 57 show the same seven tests for a 0 cm pool height and again the trends are very similar. However, this time, the point of incipience occurs at the lowest value of heat flux. Figures 58 and 59 show tube one only for all seven tests for increasing and decreasing heat flux respectively. The conclusions drawn from these figures are the same as before.

To summarize the effect of pool height, Figures 60 and 61 show tube one (i.e. Test One) at the three pool heights for increasing and decreasing heat flux. It can be seen that the zero pool height data nucleates first followed by 10 cm and then 20 cm. Similar trends were seen regardless of what test was chosen i.e. for test seven with whole bundle plus simulation heaters activated, all three points of incipience (for the 3 pool heights) move to a lower heat flux but the zero pool height data still nucleate first. Obviously, the greater pressure heads felt by the tubes at larger pool heights inhibit the transition to nucleate boiling i.e. larger wall superheats are required to overcome the increased pressure. Further experiments should be conducted in the future whereby the vapor pressure above the bundle is varied with the pool height such that the pressure that each tube "feels" at a given location is the same.

D. EFFECT OF AUXILIARY HEATERS

For all tests reported so far, the auxiliary heaters were set to 1kW nominal. The auxiliary heaters were needed to maintain pool temperature throughout the test. They were only really needed at low heat fluxes or if only a few tubes in the bundle were activated.

For these tests, if they were not used, the evaporator could not produce enough vapor to keep the pressure constant even with the condenser shut down (i.e. the walls of the test section acted as the condenser). As a consequence, the pool temperature would drop. However, the necessary operation of the auxiliary heaters has an effect on the circulation patterns within the bundle (this has been demonstrated in the single tube facility). Therefore, by having these auxiliary heaters set to the same value for each test, any effect they may have should be a constant factor. To see the effect that the auxiliary heaters have, Figure 62 shows data for three tubes on during a decreasing heat flux with the auxiliary heaters off compared to Figure 18 with them set at 1 kW for a 10 cm pool height. Essentially the effect is minimal in the nucleate region at high heat fluxes. At lower heat fluxes, no data could be taken with the auxiliary heaters off. In the convection region (again at low heat flux so there is no data with the auxiliary heaters off), the effects of increasing the auxiliary heater power is to increase the heat-transfer coefficient (i.e. reducing the wall superheat). The same effect was seen for four tubes with the auxiliary heaters off and set to 1 kW for a 10 cm pool height; shown in Figures 63 and 20 respectively. Figures 64 and 30 show the same trend for tube one with the auxiliary heaters set at 3 kW compared to 1 kW for a pool height of 20 cm. These trends are probably seen due to the increased circulation within the bundle at the higher auxiliary heater setting. Obviously, it would be preferable to do away with the auxiliary heaters altogether. With R-114, due to the lower normal boiling point, this should be possible.

E. NUCLEATION SITE ACTIVATION/DEACTIVATION

Nucleation site activation/deactivation is not well understood. Once a tube is nucleating, there are a couple of ways that the nucleation sites can die out:

1. Reducing the heat to the tube surface thereby allowing the fluid to collapse the vapor bubble and re-wet the surface due to pressure effects.

2. Increasing the subcooling of the liquid around the tube (i.e. causing the vapor bubble to condense into the fluid).

The following tests were conducted to see how quickly the nucleation sites, once activated, died away if the power to the tube was cut off (i.e. to see how quickly the liquid re-wets the surface as discussed in mechanism one above). The pool temperature was maintained at saturation conditions throughout the test (i.e. there was no subcooling). All the tests were conducted on the top tube only. The test procedure used was the modified surface preparation B. The power to the heater was then turned off for a known finite time and then reactivated. An increasing run was then carried out. This was repeated for a number of different times and pool heights. The auxiliary power setting was 1 kW for all tests.

Figures 65 and 66 show the data for a pool height of 20 cm. The turn-off time for the heater varied between five seconds and one hour. It can be seen that after only 15 s, the nucleation sites have all died out and the tube behaves as if it had been secured overnight (these are the data sets listed as 14 and 15 hours). Of course, by securing overnight, subcooling also plays a part in deactivating the sites.

Figure 67 shows the data for a pool height of 10 cm. The turn-off time for the heater varied between five seconds and one minute. It can be seen that after one minute, the nucleation sites have all died out and the tube behaves as if it had been secured overnight. Hence, it would seem that due to the reduced pressure head trying to push the liquid into the sites, the time needed to deactivate all the sites is significantly longer.

Figures 68 and 69 show the data for a pool height of 0 cm. The turn-off time for the heater varied between 40 seconds and 8 hours (keeping pool temperature constant throughout). It can be seen that even for a shut-off time of 8 hours, none of the nucleation sites are deactivated. The pressure head is negligible here and it is mechanism two that

deactivates the sites. As the pool temperature was not subcooled during this particular test, none of the sites are therefore deactivated. Figure 70 shows a test where the apparatus was secured for 2.75 hours (i.e. allowed to subcool). The deactivation seen is due to the subcooling that has occurred.

Similar trends for all three pool heights have been obtained for an auxiliary heater power setting of 3 kW. Slight differences in the times needed for total deactivation were noted to be 20 seconds for 10 cm vice one minute. These data are shown in Figures 71 to 75.

F. COMPARISONS WITH PREVIOUS NPS DATA

Figure 76 shows a comparison between the present data for a Turbo-B bundle in R-113 and the data of Anderson [Ref. 7] for a smooth tube bundle in R-113. For clarity, only the top tube has been shown for a decreasing heat flux. It can be seen that the heat transfer enhancement given by the enhanced tube is three to five times for high and low heat fluxes respectively.

This is also true for the overall bundle heat transfer coefficient, giving a factor of 4 enhancement at a typical operating heat flux of 20,000 W/m^2. Also shown on the figure is the correlation of Stephan and Abdelsalam [Ref. 26] showing a fairly good agreement with the smooth tube data.

Figure 77 shows a comparison between the present data and that of Eraydin [Ref. 9] who used a Turbo-B bundle in R-114. It can be seen that there is very little difference between the two sets of data. The R-114 data giving the slightly better performance. This could be due to the slightly better thermal conductivity of R-114 at its saturation temperature compared to R-113 at its saturation temperature.

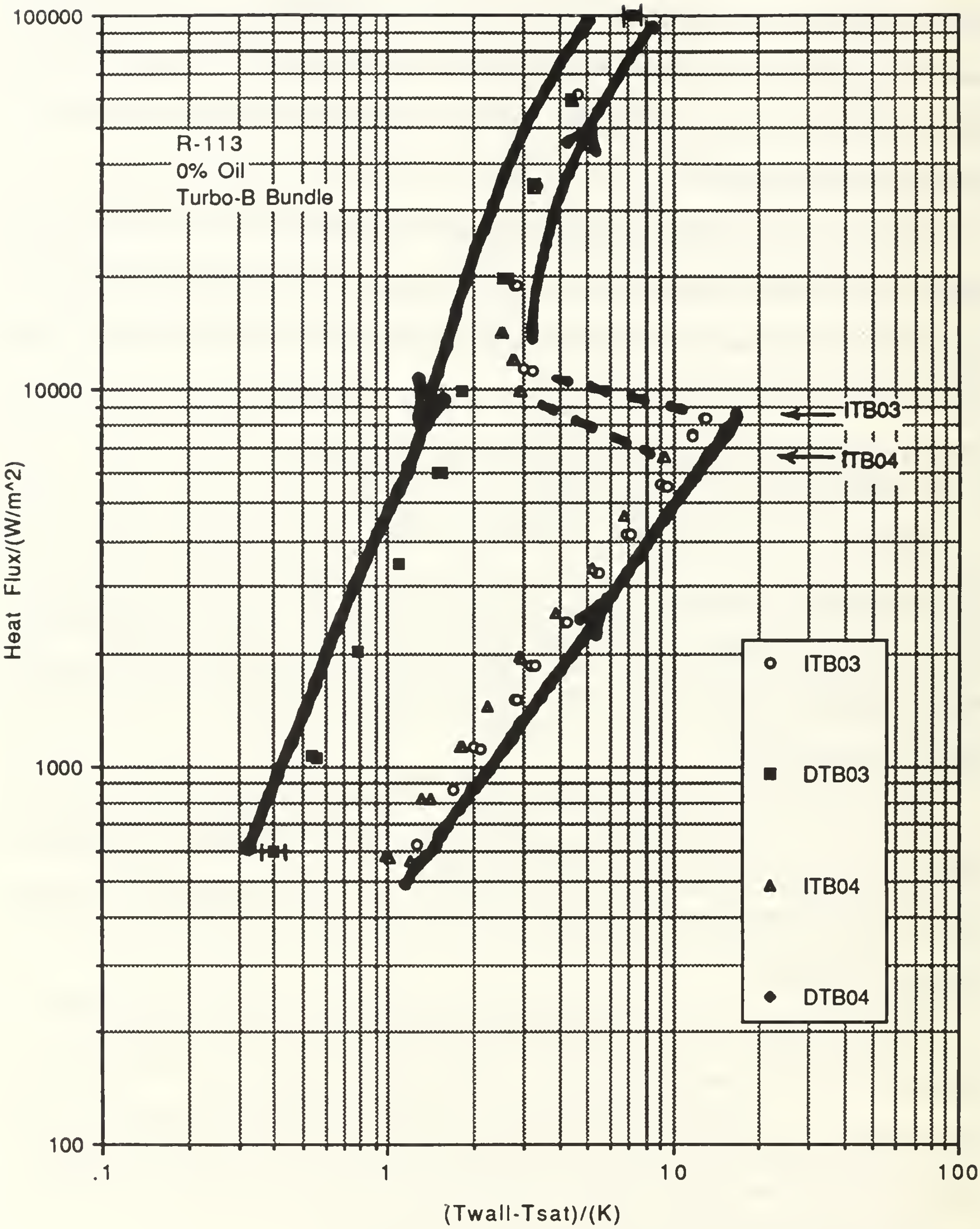

Figure 13. Performance of Tube 1 at a 10 cm Pool Height for Similar Data Taken on Different Days to Show Repeatability

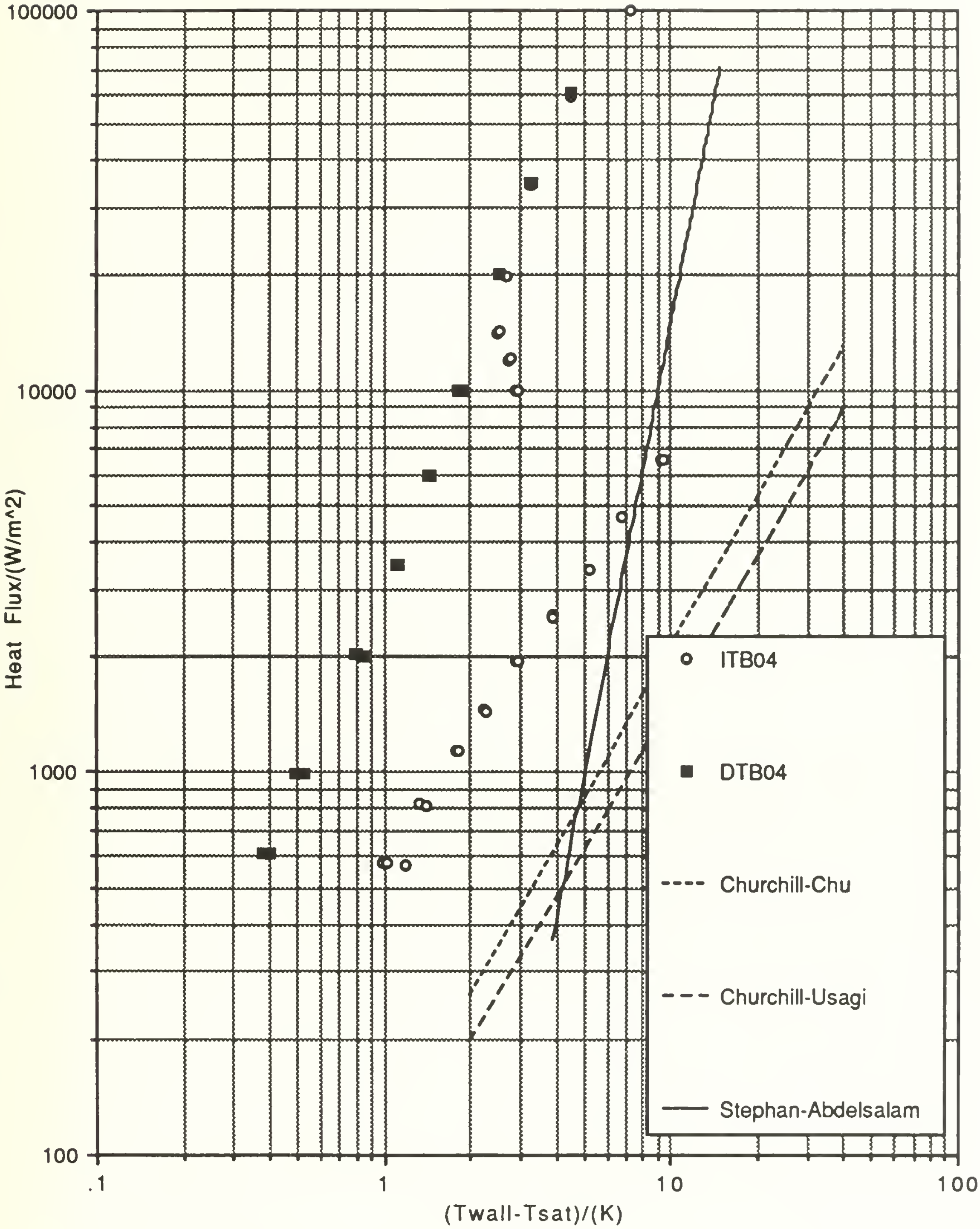

Figure 14. Performance of Tube 1 at a 10 cm Pool Height Along With Correlations for Natural Convection and Nucleate Pool Boiling Regions

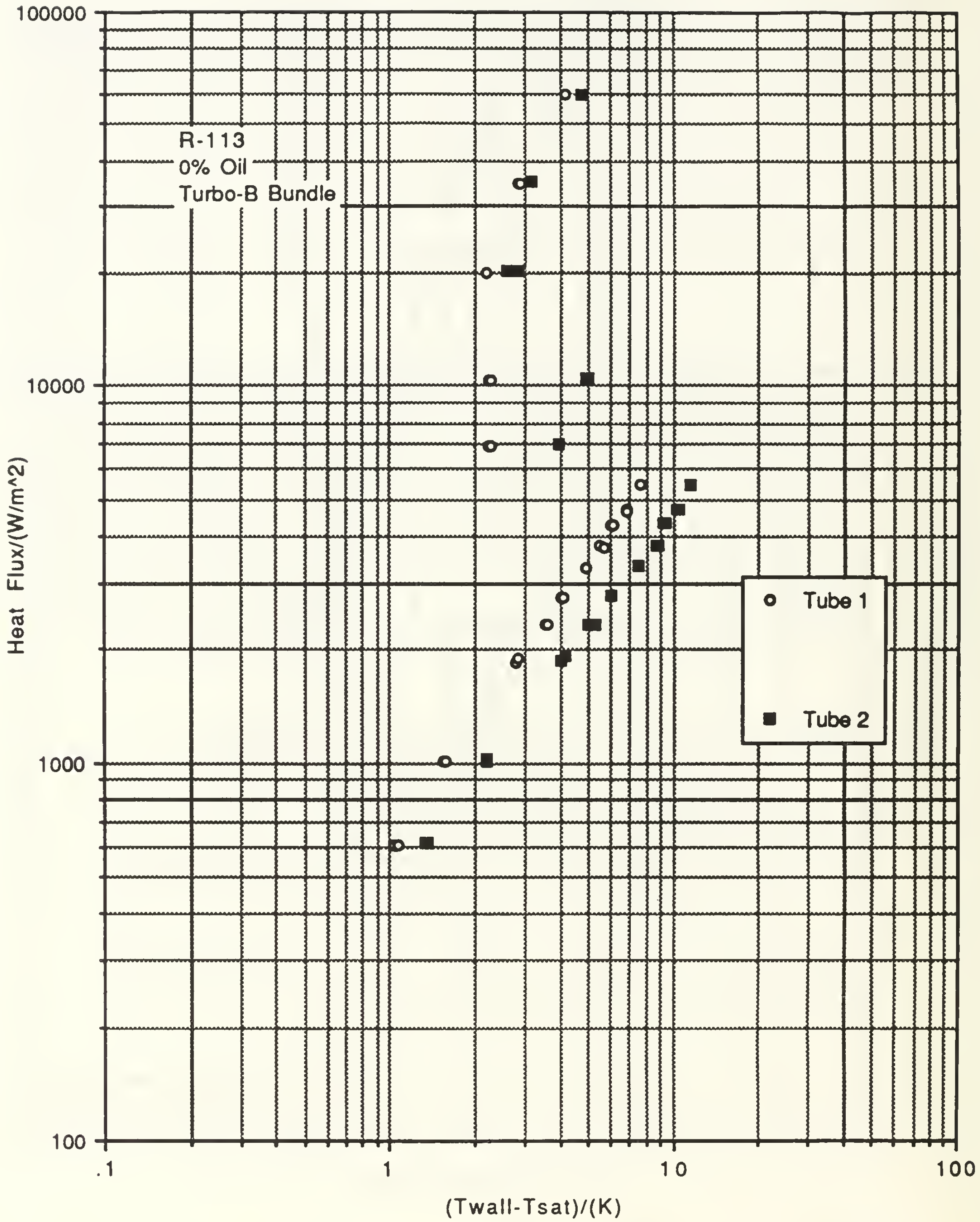

Figure 15. Performance Variation of Tubes 1&2 at a 10 cm Pool Height During a Increasing Heat Flux (ITB05)

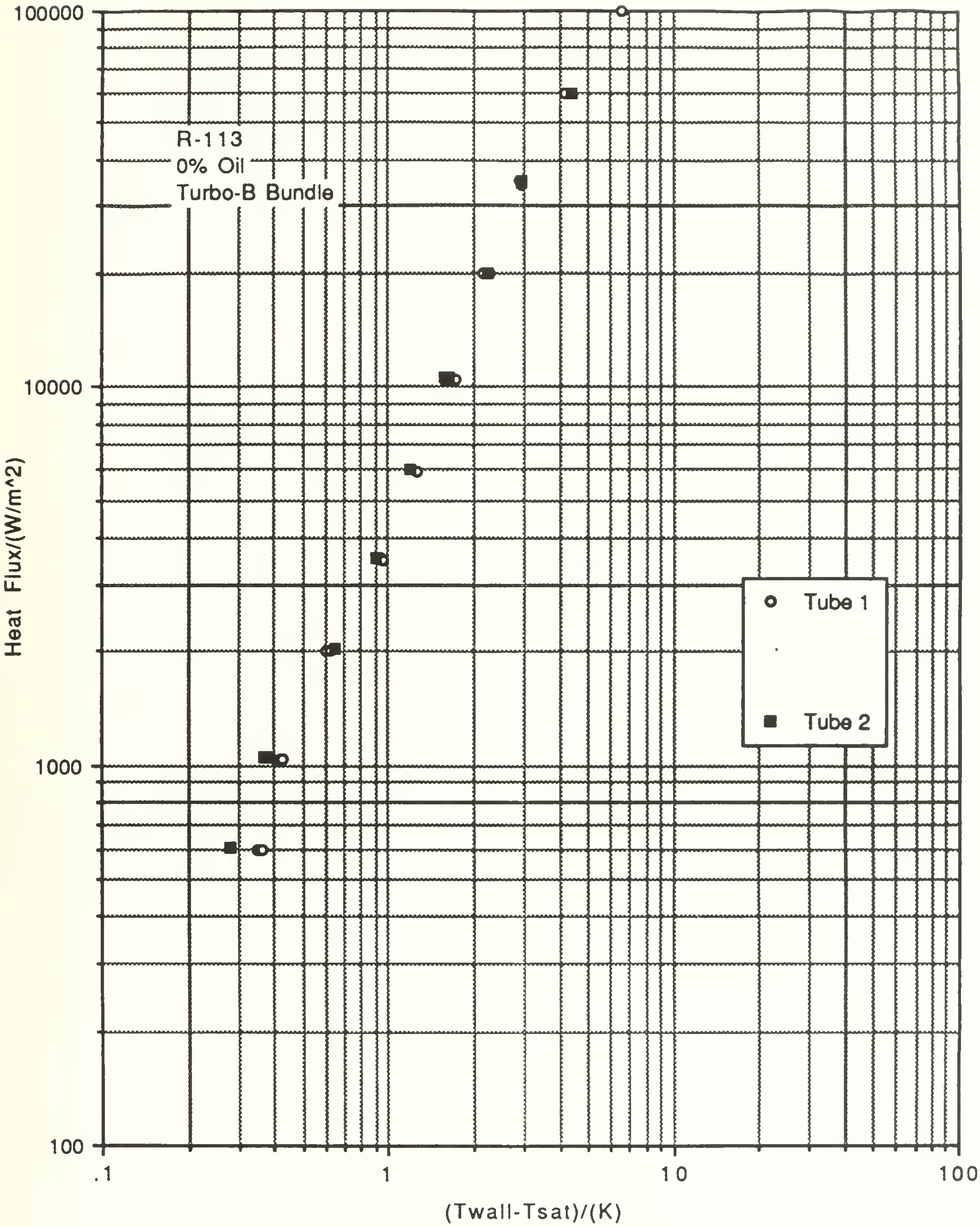

Figure 16. Performance Variation of Tubes 1&2 at a 10 cm Pool Height During a Decreasing Heat Flux (DTB05)

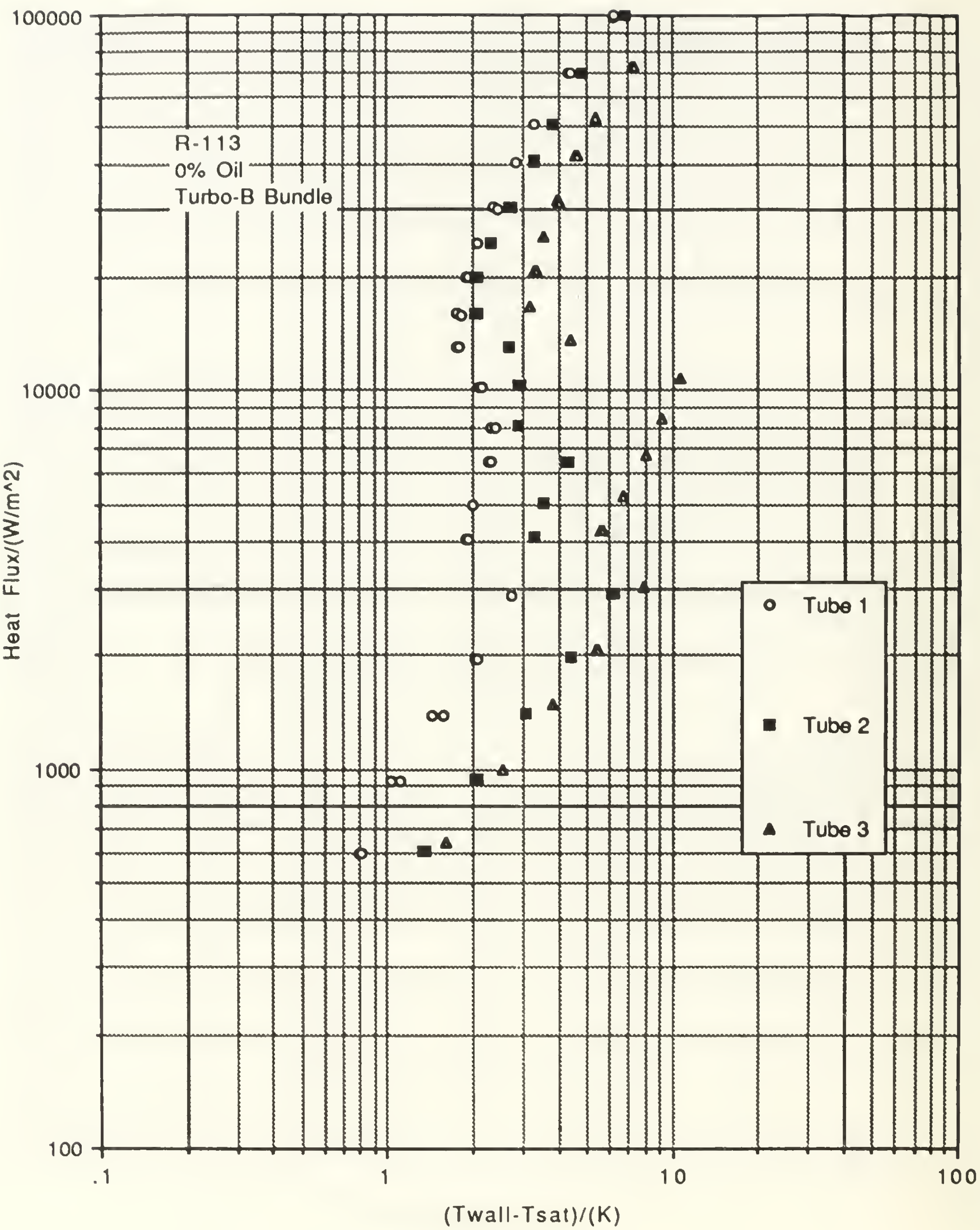

Figure 17. Performance Variation of Tubes 1 to 3 at a 10 cm Pool Height During a Increasing Heat Flux (ITB06)

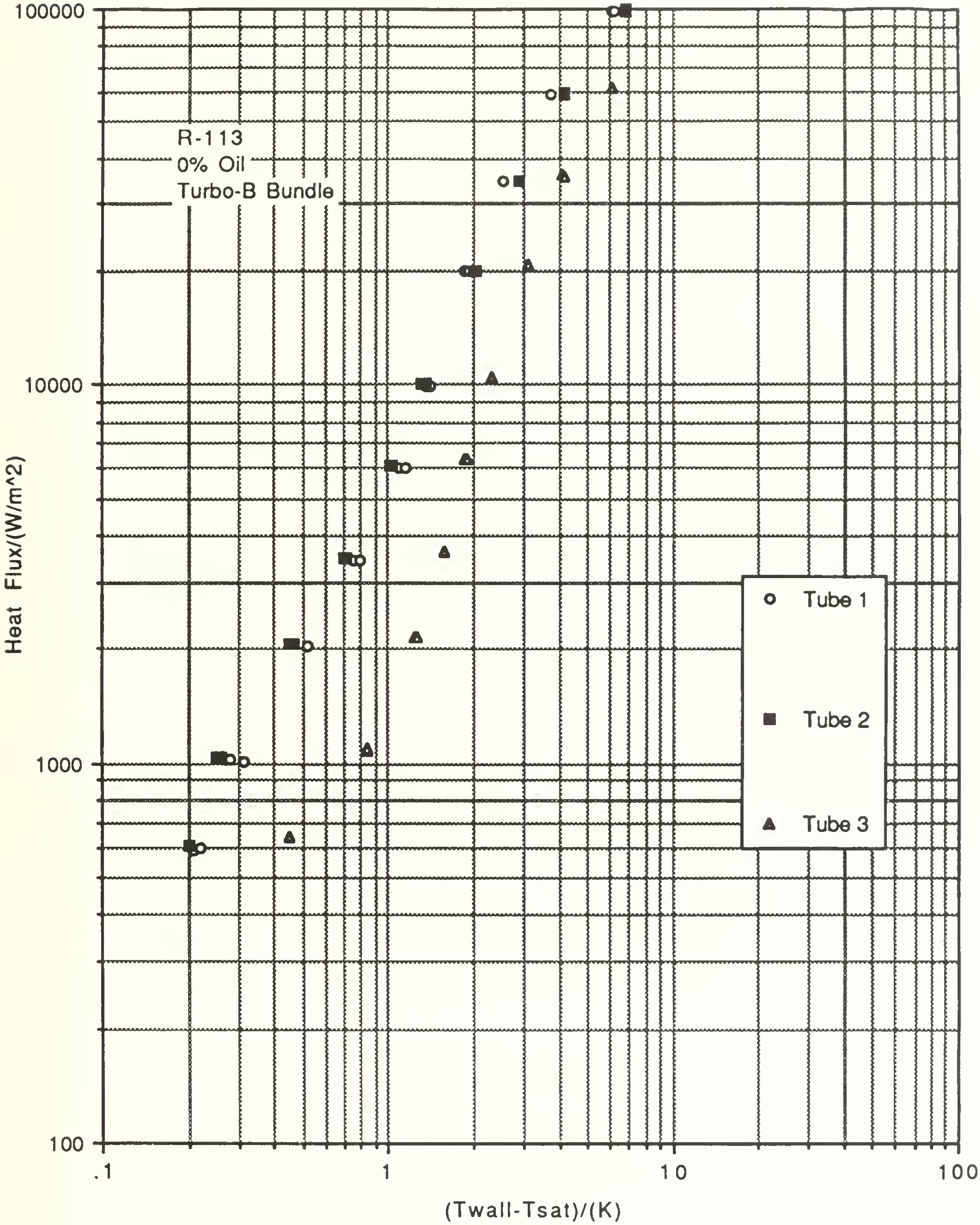

Figure 18. Performance Variation of Tubes 1 to 3 at a 10 cm Pool Height During a Decreasing Heat Flux (DTB06)

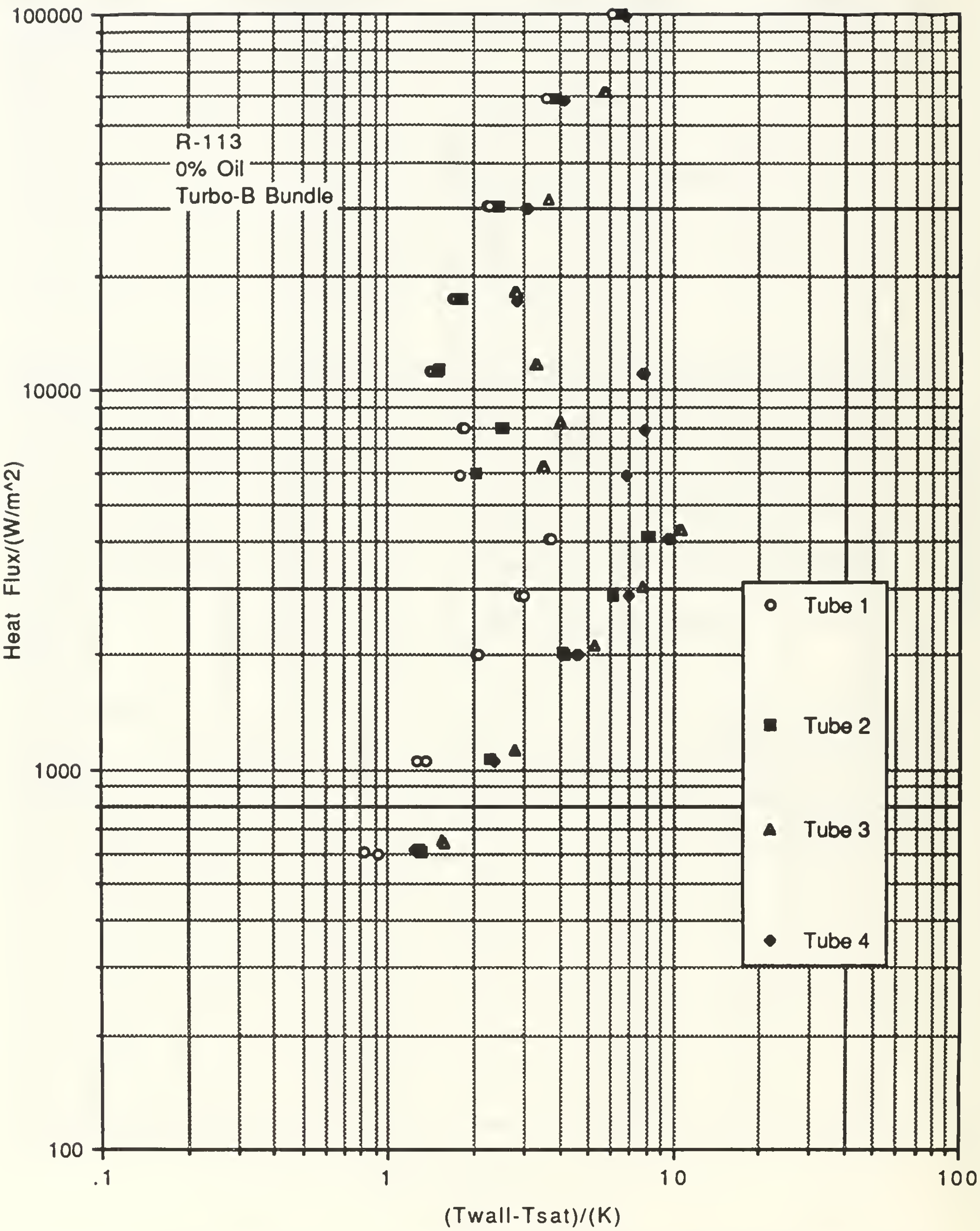

Figure 19. Performance Variation of Tubes 1 to 4 at a 10 cm Pool Height During a Increasing Heat Flux (ITB07)

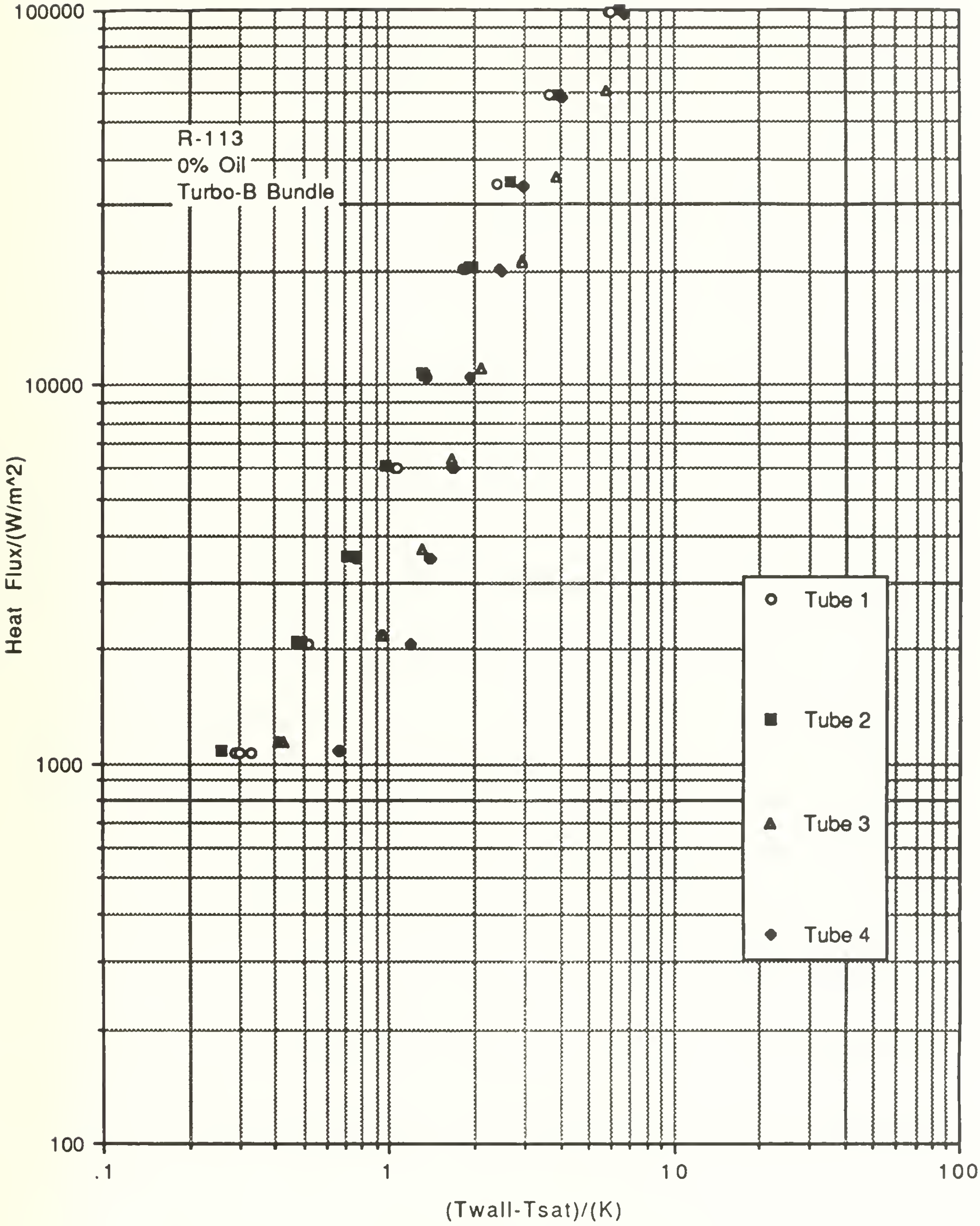

Figure 20. Performance Variation of Tubes 1 to 4 at a 10 cm Pool Height During a Decreasing Heat Flux (DTB07)

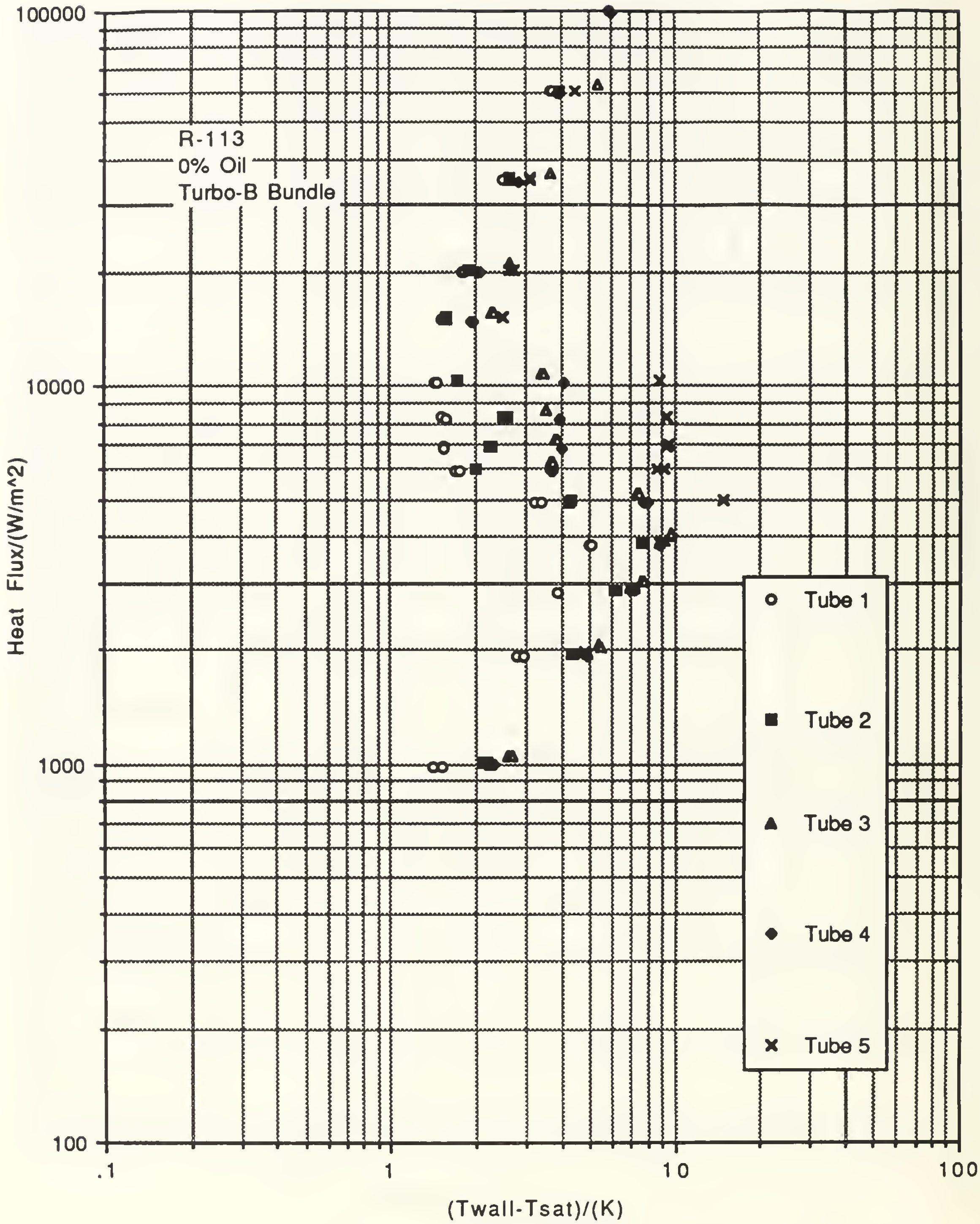

Figure 21. Performance Variation of Tubes 1 to 5 at a 10 cm Pool Height During a Increasing Heat Flux (ITB27)

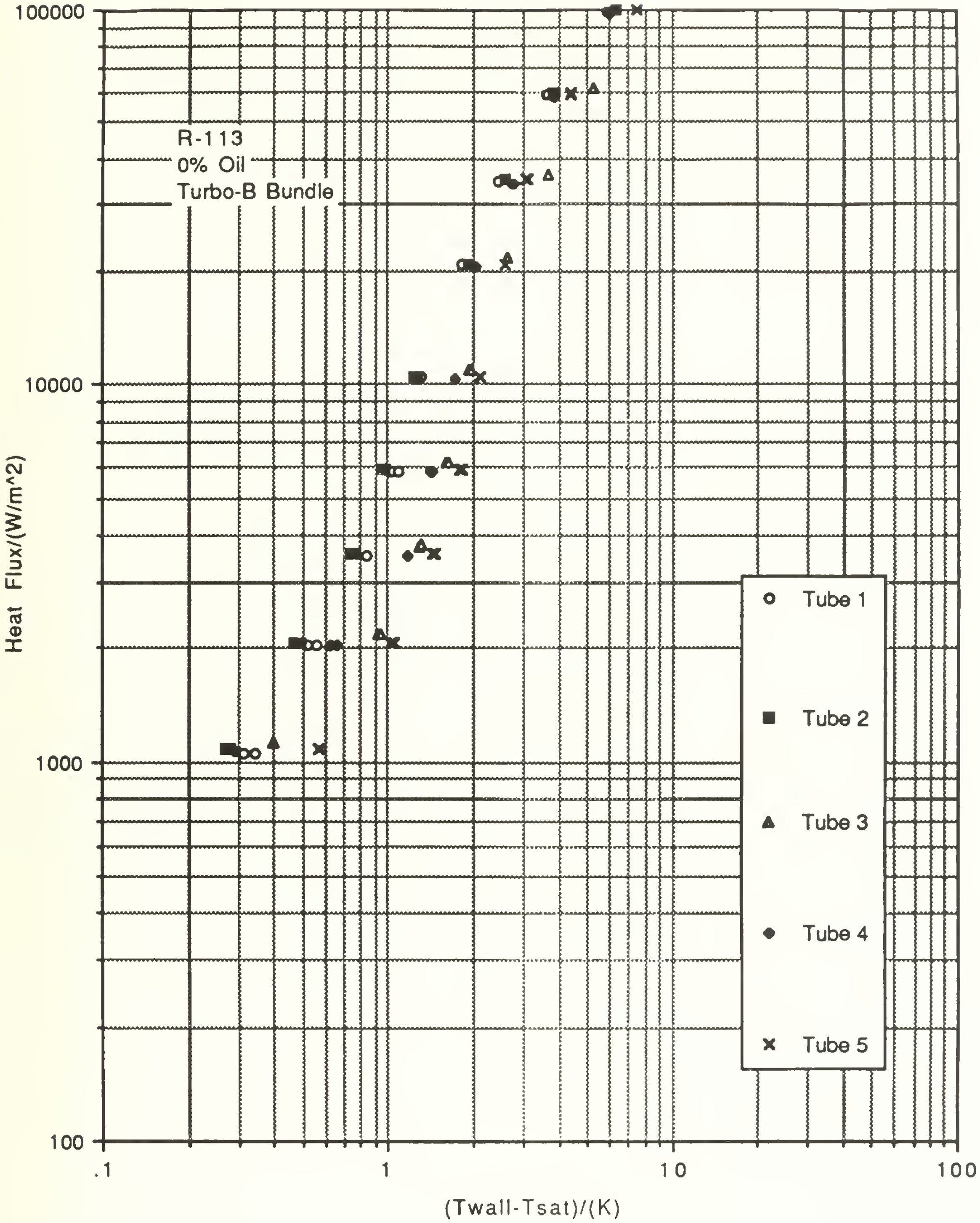

Figure 22. Performance Variation of Tubes 1 to 5 at a 10 cm Pool Height During a Decreasing Heat Flux (DTB27)

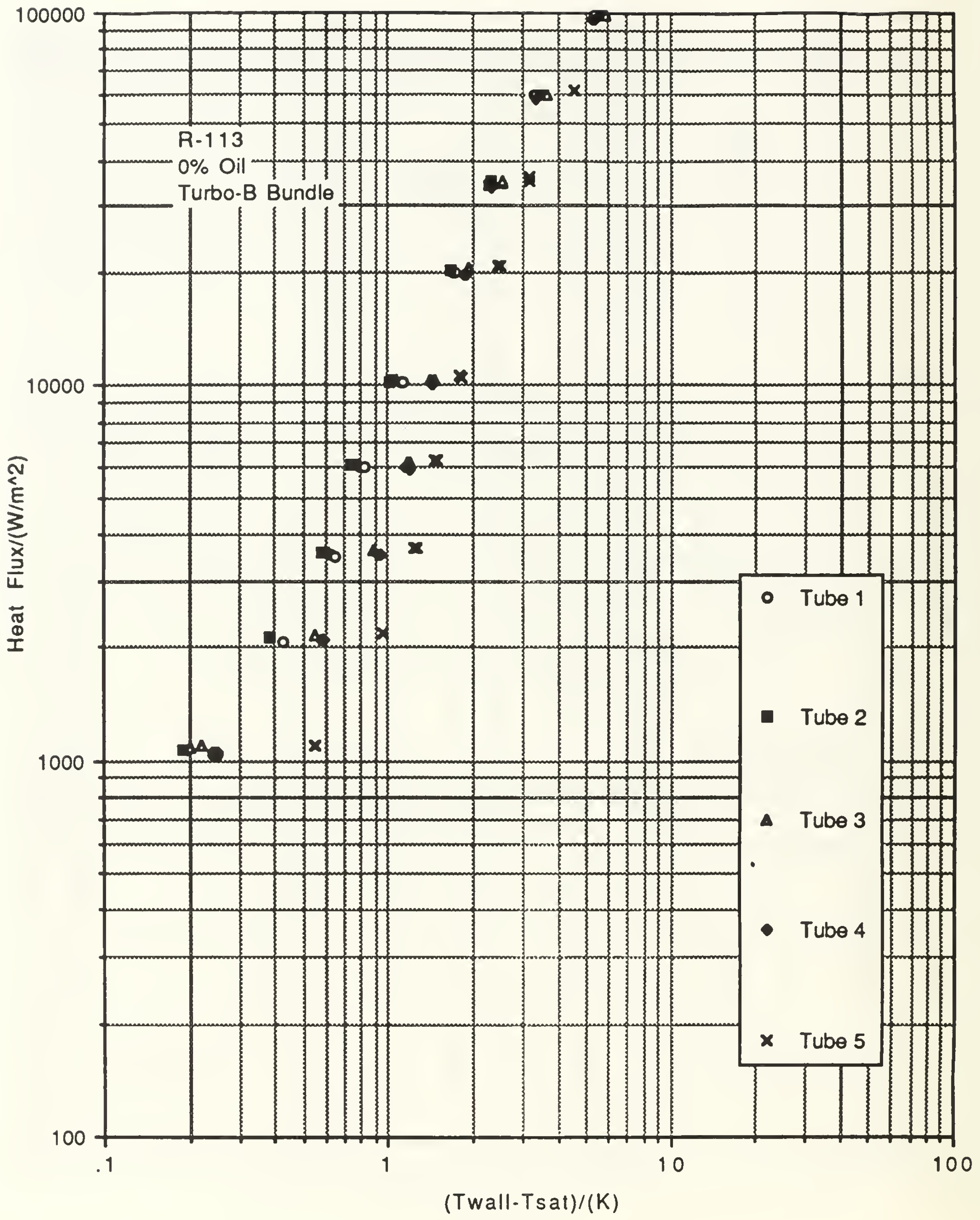

Figure 23. Performance Variation of Tubes 1 to 5 at a 10 cm Pool Height During a Decreasing Heat Flux with Tubes 3&5 Switched (DTB30)

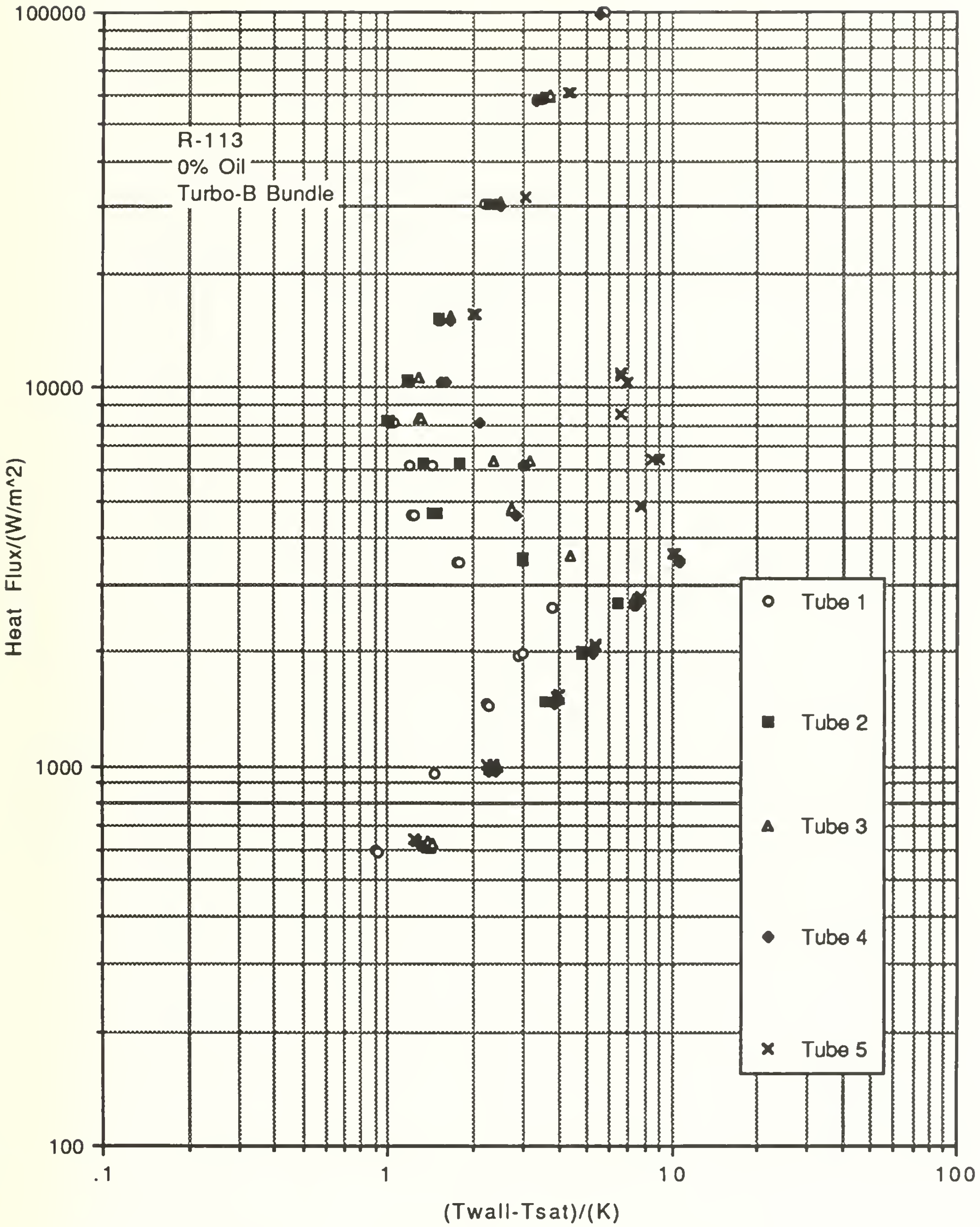

Figure 24. Performance Variation of the Bundle at a 10 cm Pool Height During a Increasing Heat Flux (ITB48)

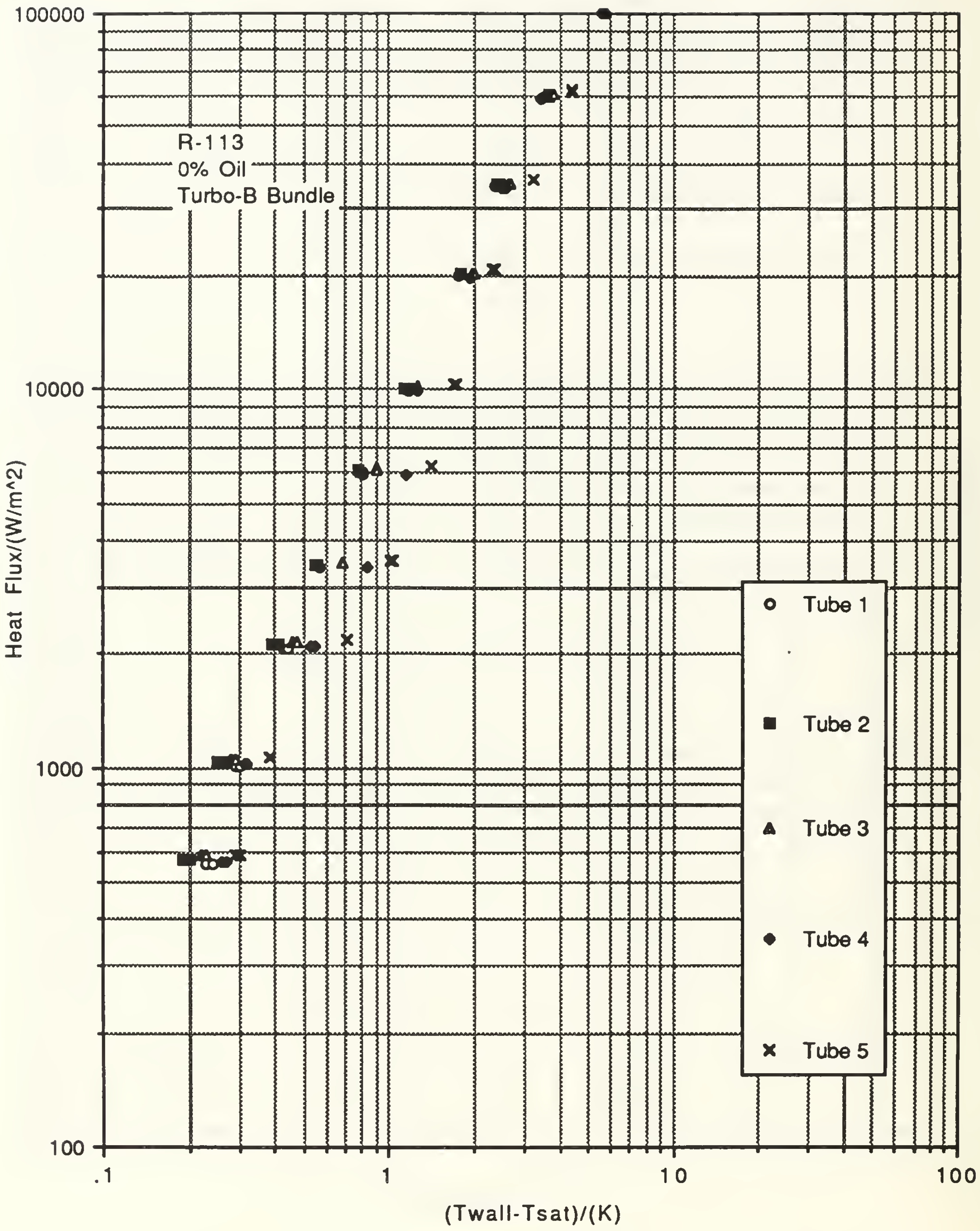

Figure 25. Performance Variation of the Bundle at a 10 cm Pool Height During a Decreasing Heat Flux (DTB48)

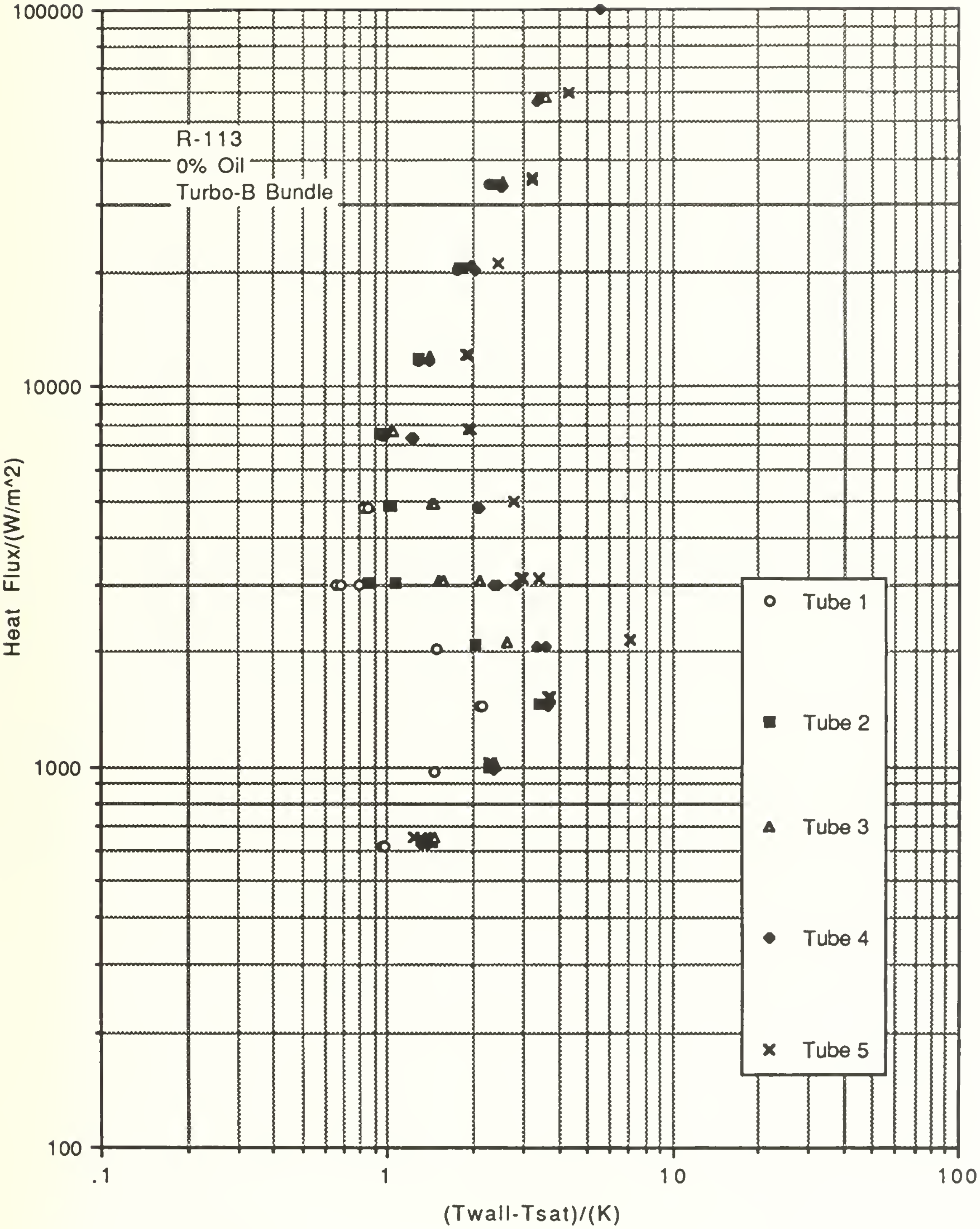

Figure 26. Performance Variation of the Bundle plus Simulation Heaters at a 10 cm Pool Height During a Increasing Heat Flux (ITB49)

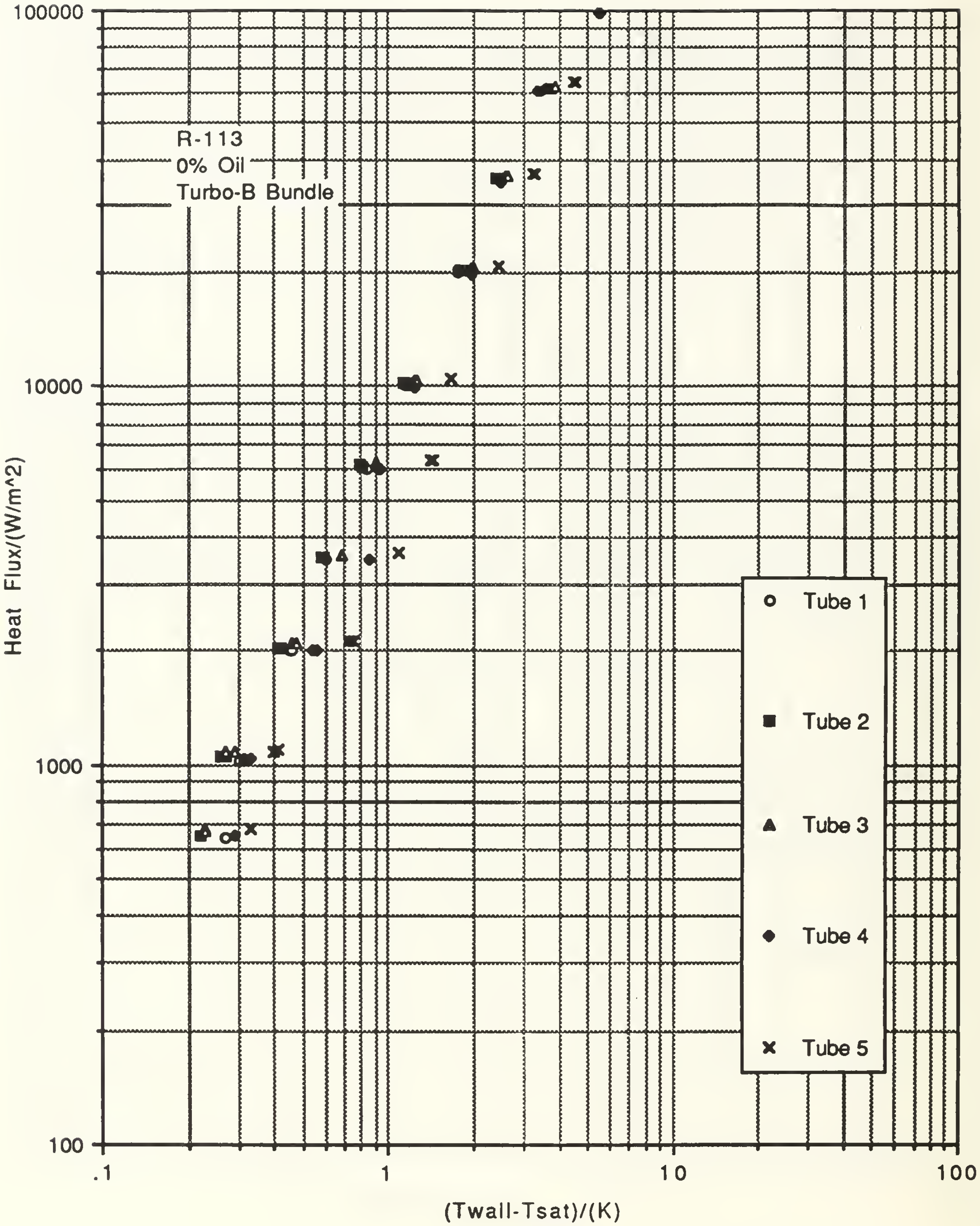

Figure 27. Performance Variation of the Bundle plus Simulation Heaters at a 10 cm Pool Height During a Decreasing Heat Flux (DTB49)

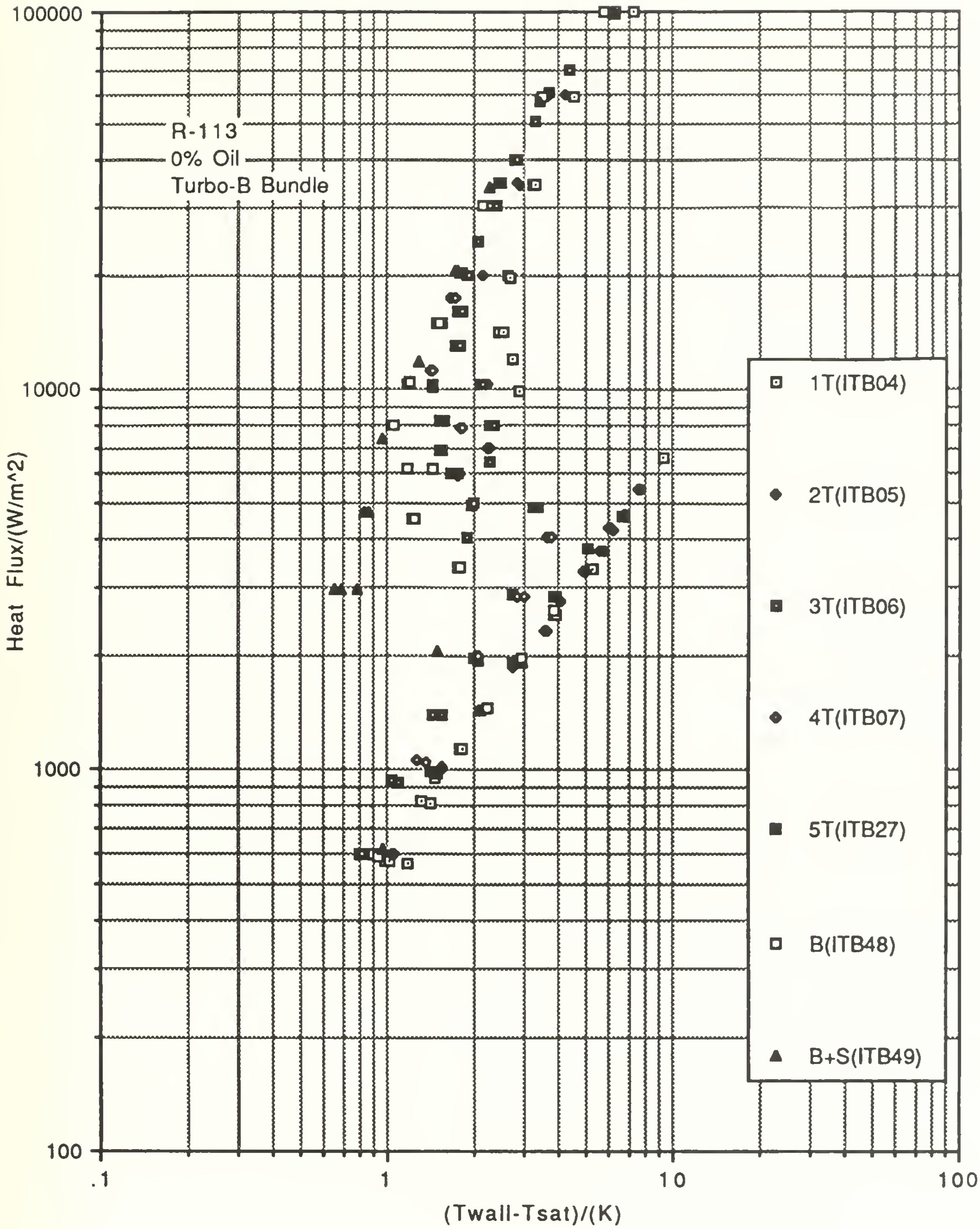

Figure 28. 10 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influenced by a Increasing Number of Heated Tubes in a Turbo-B Bundle During a Increasing Heat Flux

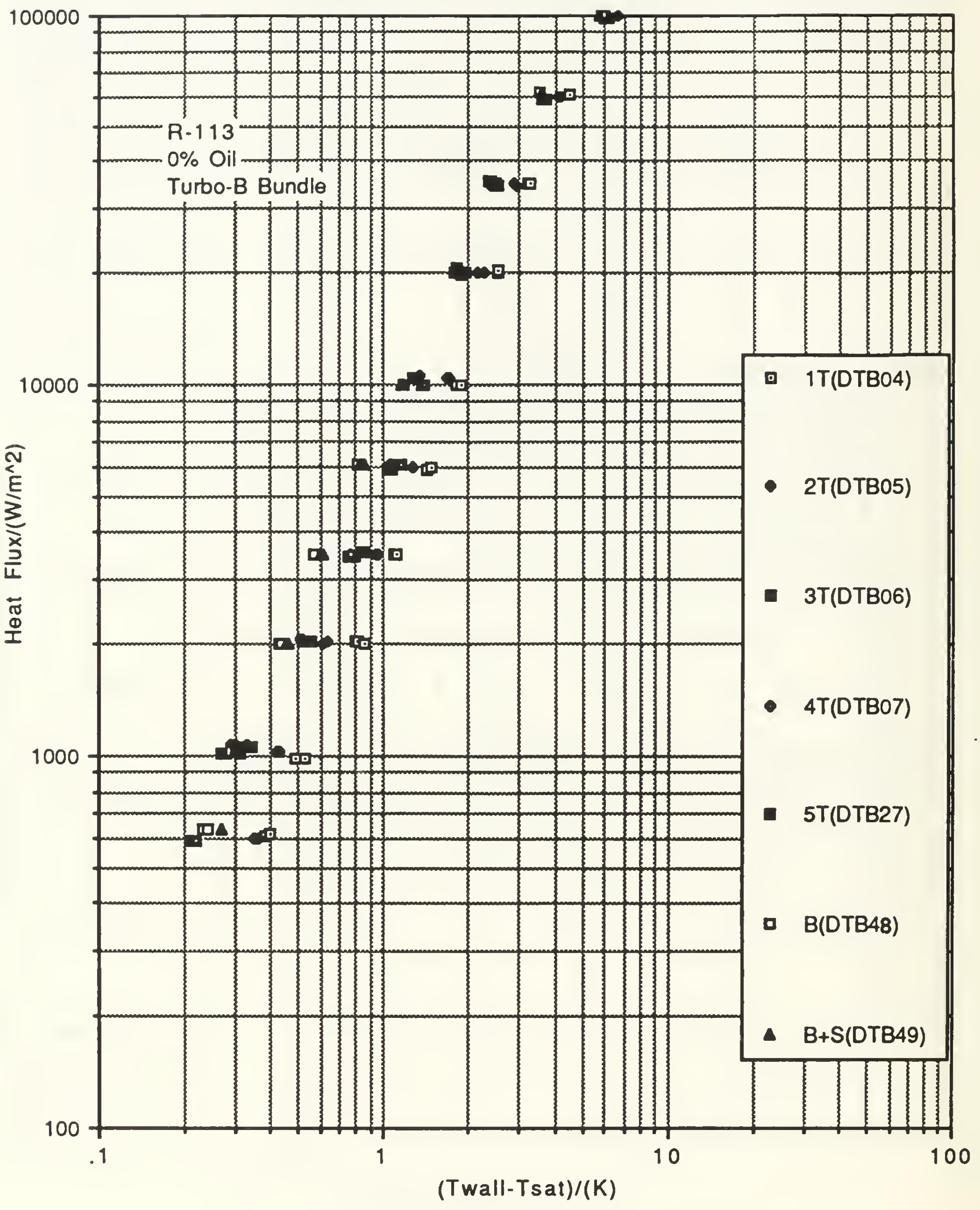

Figure 29. 10 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influence by a Increasing Number of Heated Tubes in a Turbo-B Bundle During a Decreasing Heat Flux

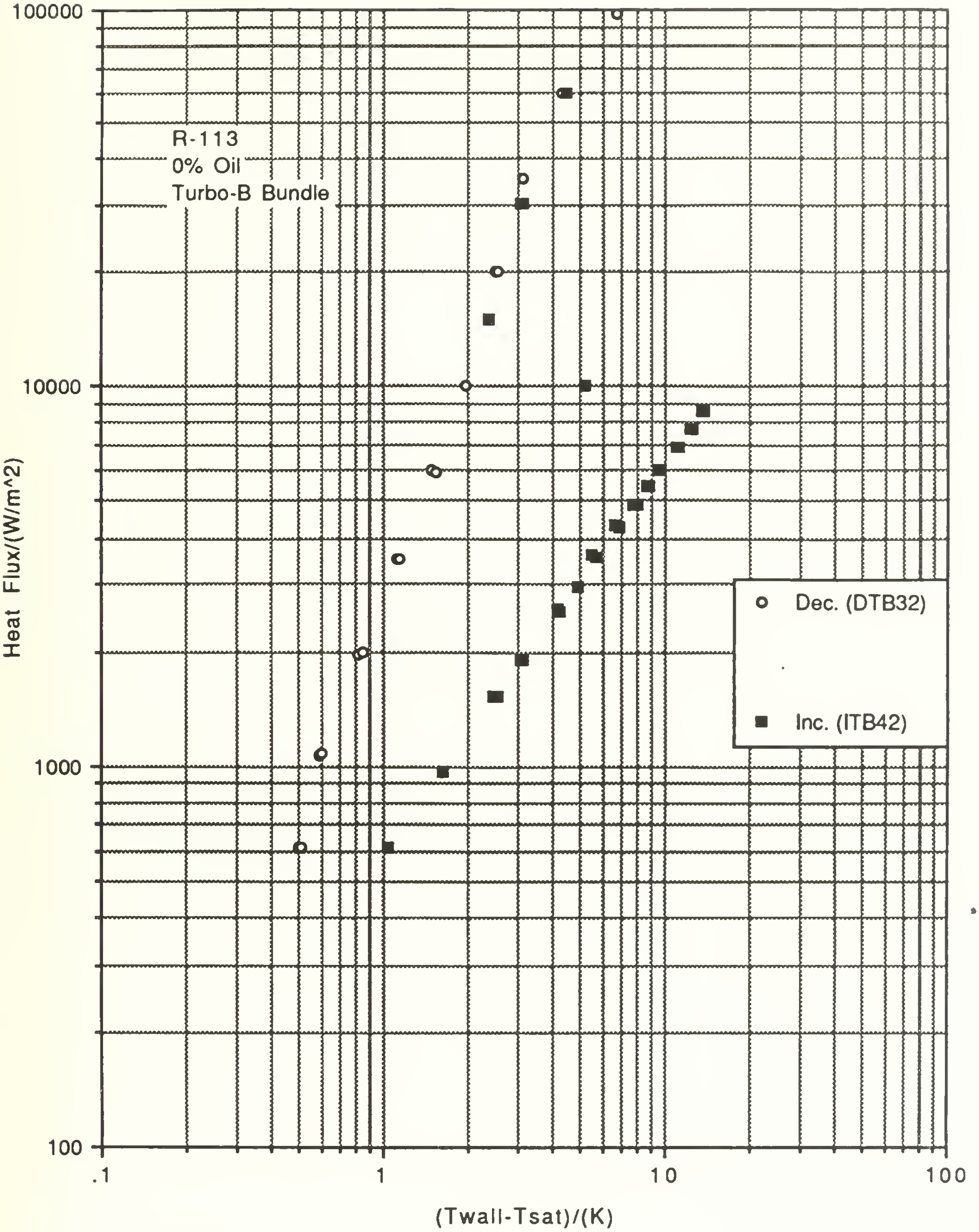

Figure 30. Performance of Tube 1 at a 20 cm Pool Height

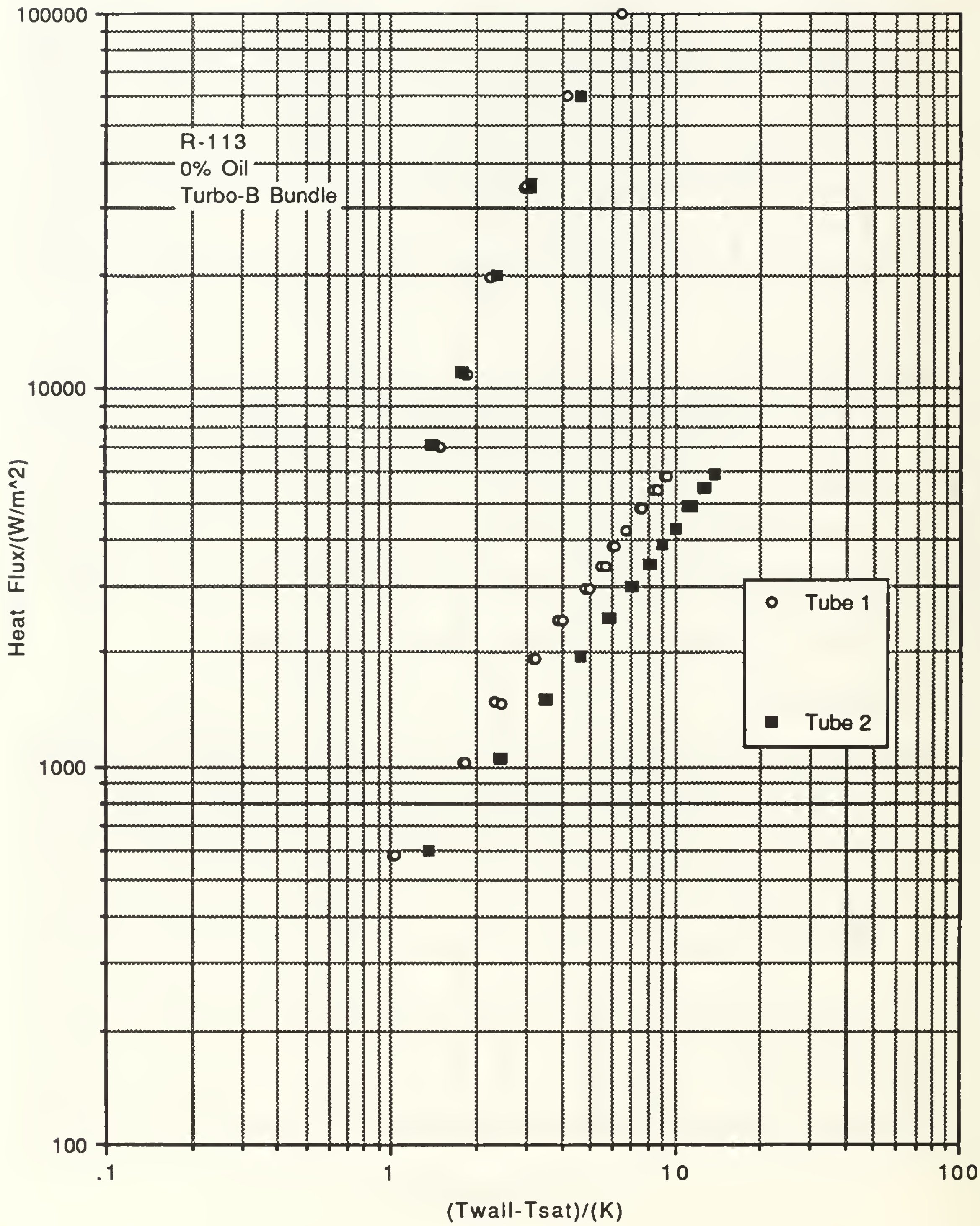

Figure 31. Performance Variation of Tubes 1&2 at a 20 cm Pool Height During a Increasing Heat Flux (ITB34)

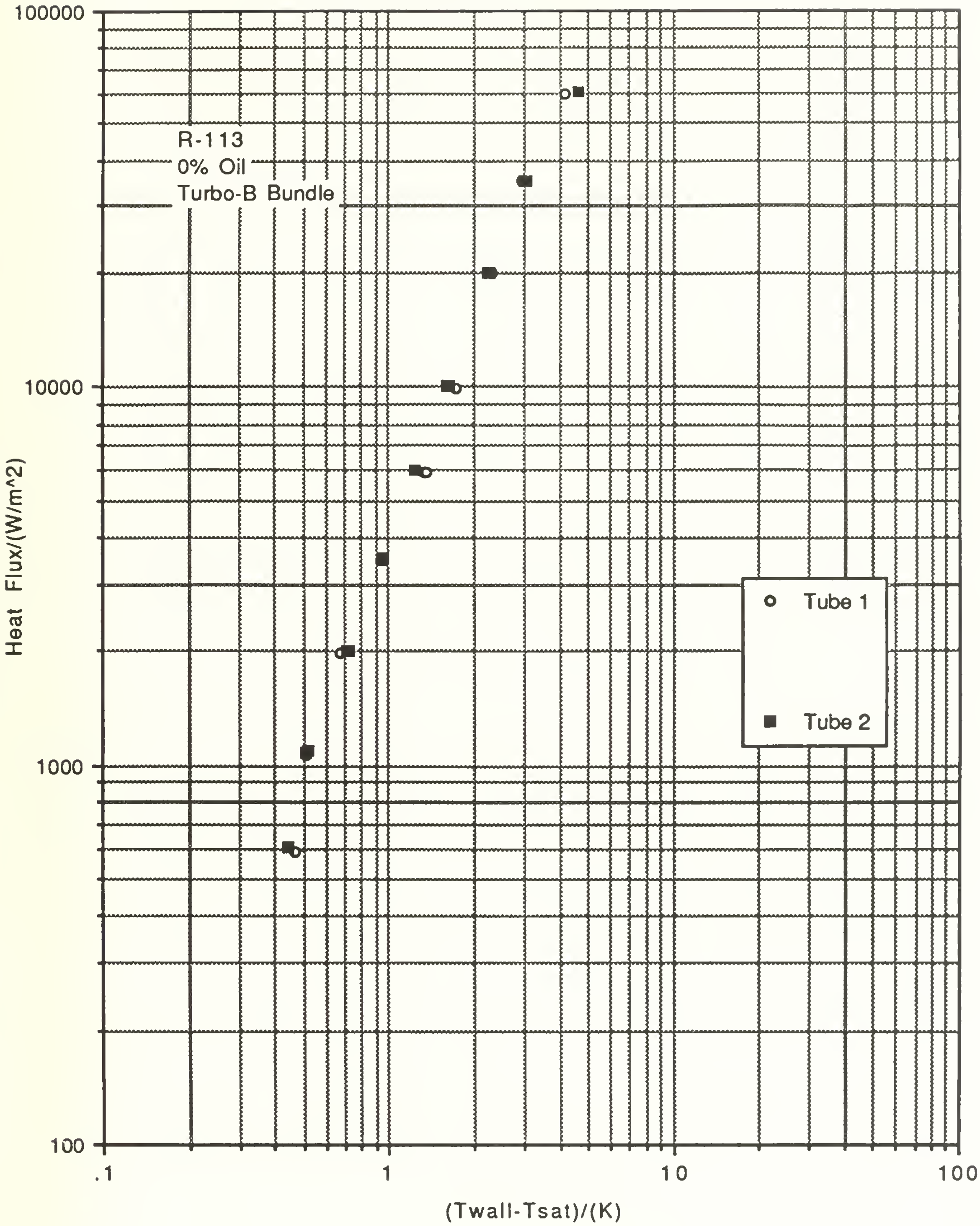

Figure 32. Performance Variation of Tubes 1&2 at a 20 cm Pool Height During a Decreasing Heat Flux (DTB34)

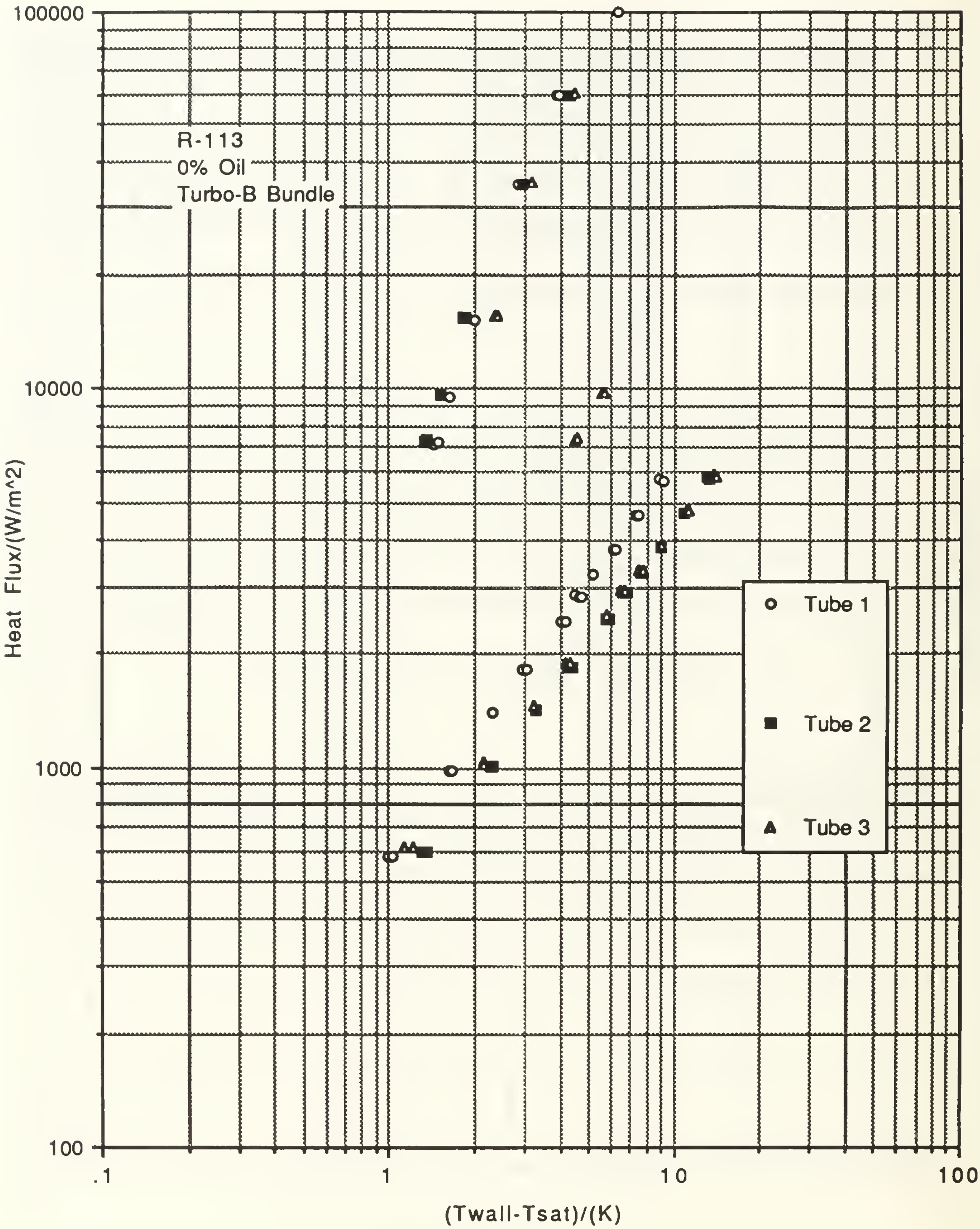

Figure 33. Performance Variation of Tubes 1 to 3 at a 20 cm Pool Height During a Increasing Heat Flux (ITB35)

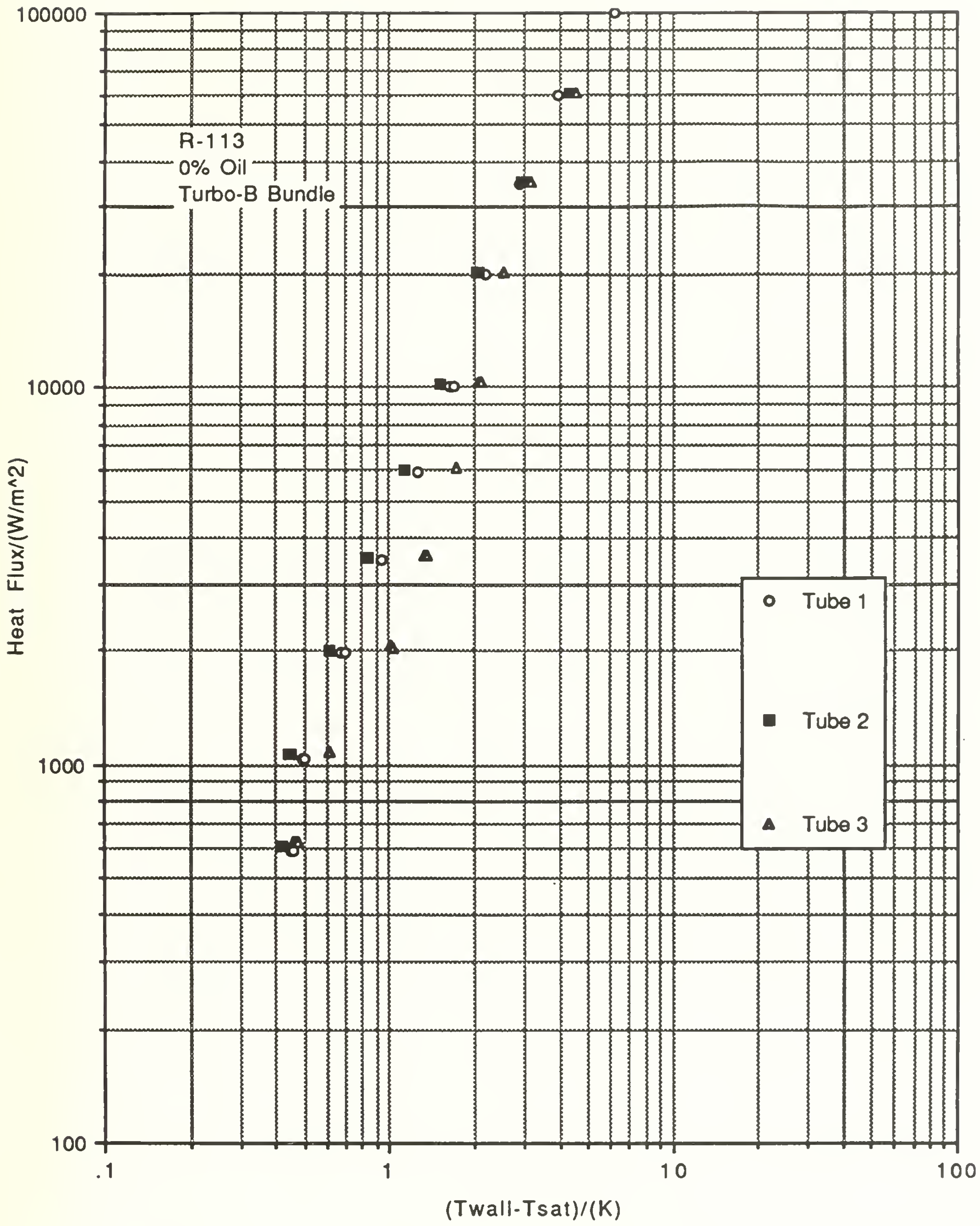

Figure 34. Performance Variation of Tubes 1 to 3 at a 20 cm Pool Height During a Decreasing Heat Flux (DTB35)

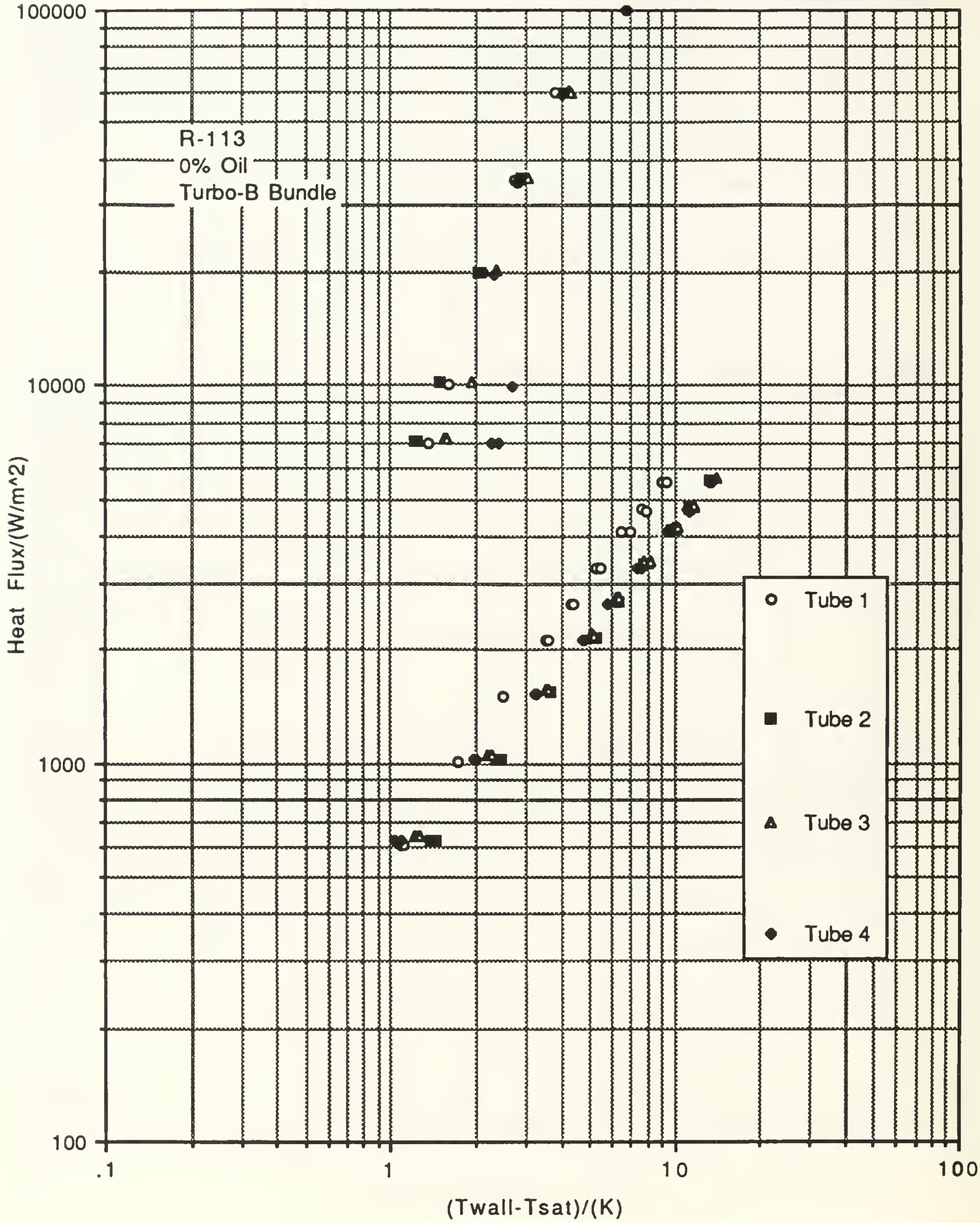

Figure 35. Performance Variation of Tubes 1 to 4 at a 20 cm Pool Height During a Increasing Heat Flux (ITB36)

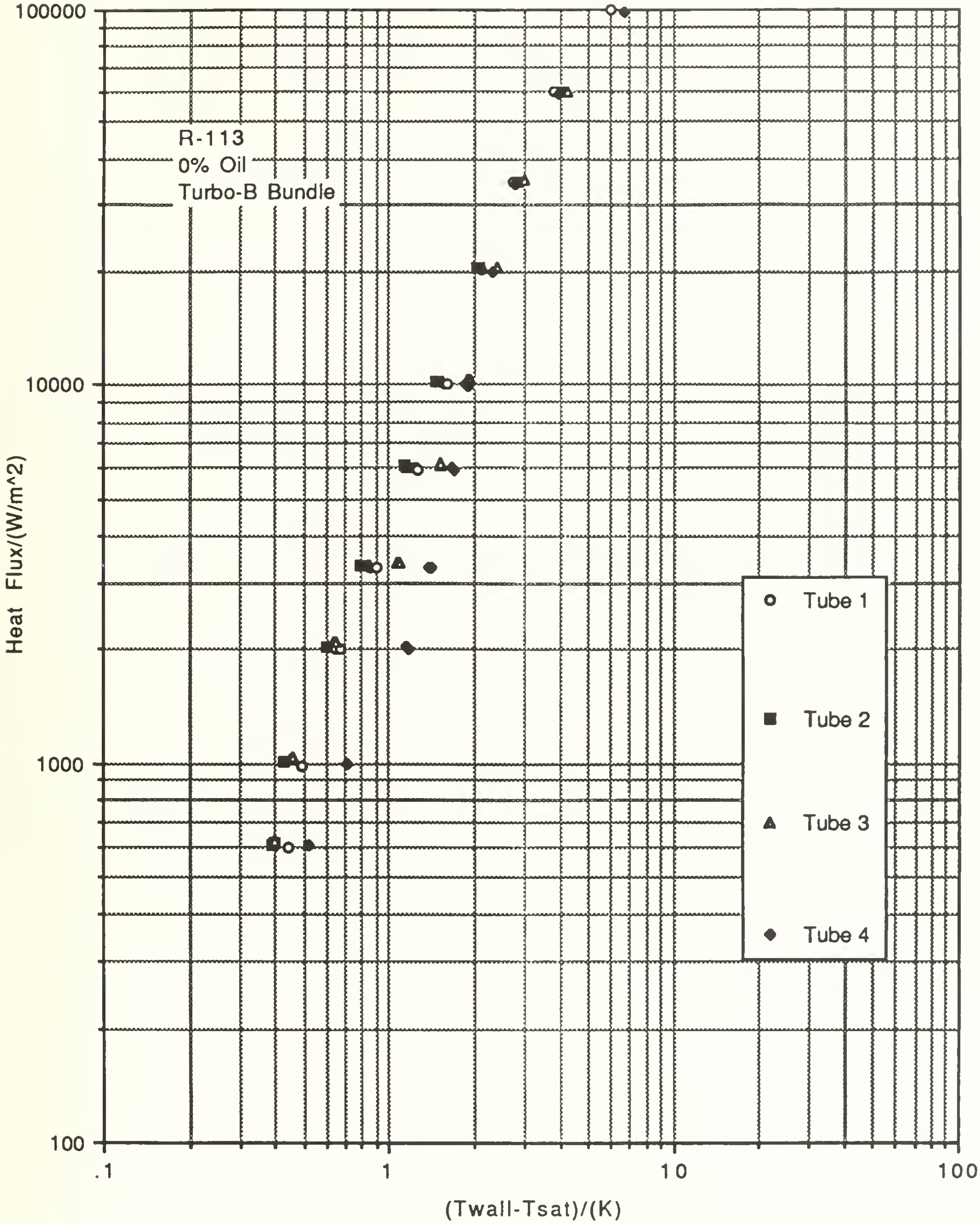

Figure 36. Performance Variation of Tubes 1 to 4 at a 20 cm Pool Height During a Decreasing Heat Flux (DTB36)

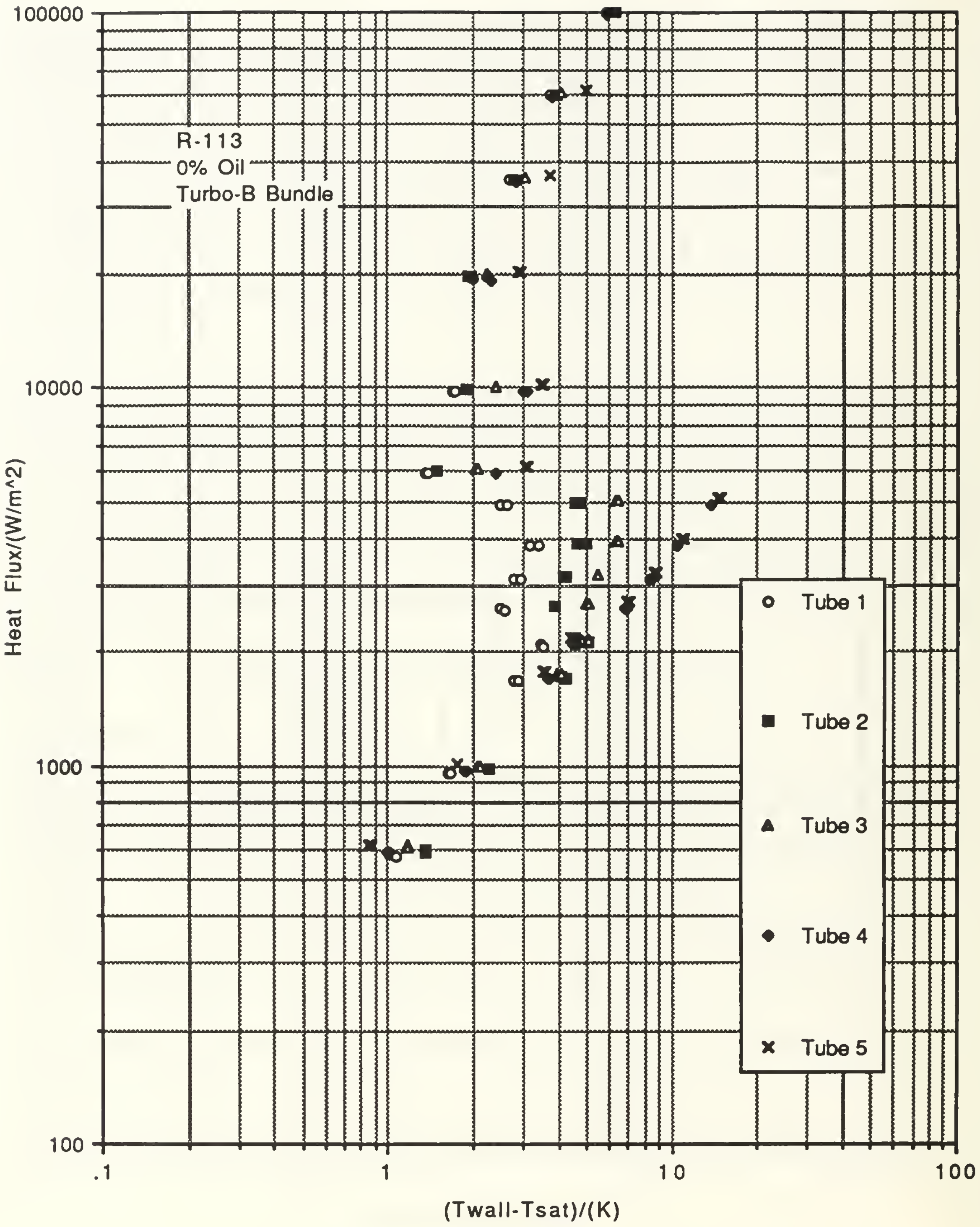

Figure 37. Performance Variation of Tubes 1 to 5 at a 20 cm Pool Height During a Increasing Heat Flux (ITB37)

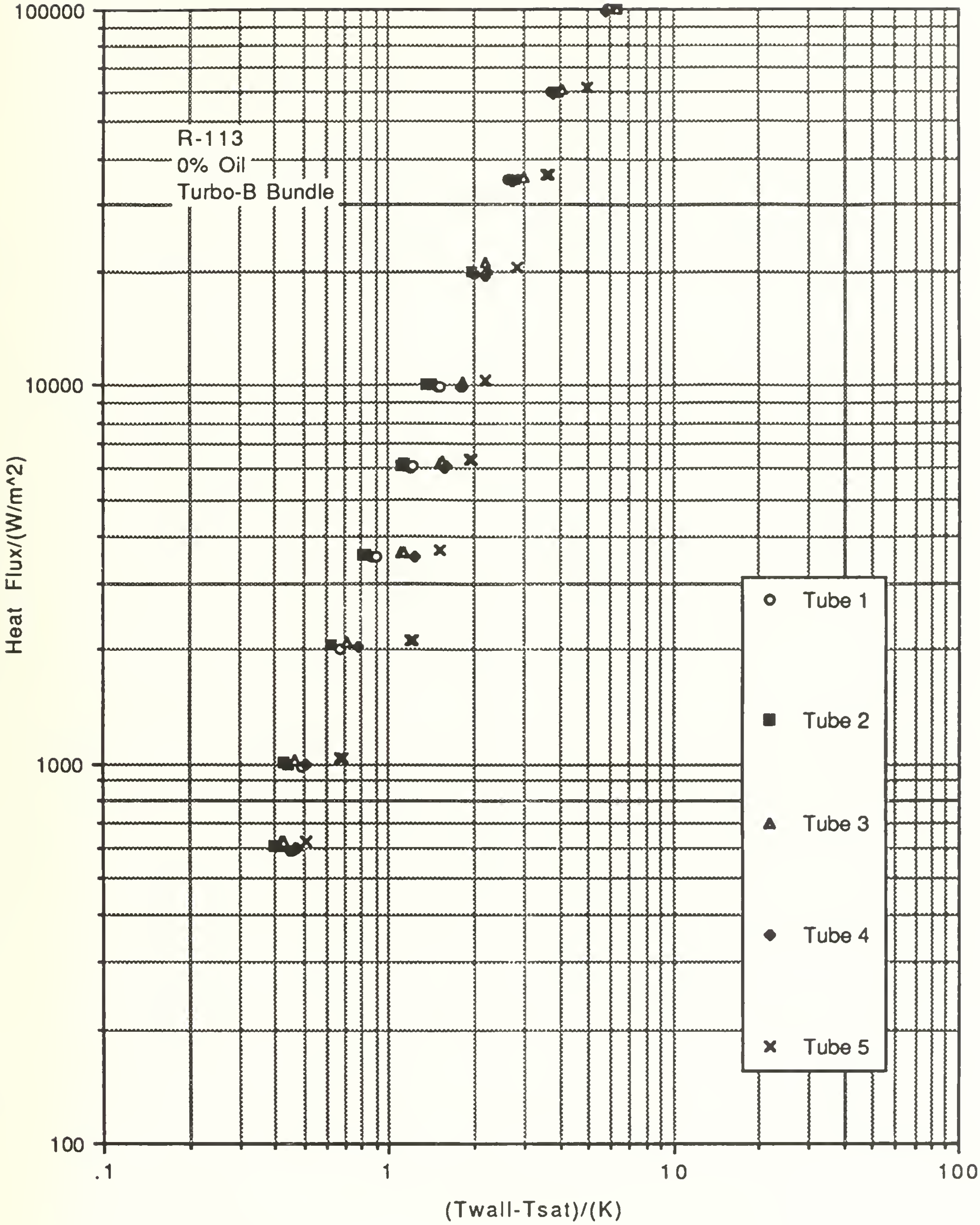

Figure 38. Performance Variation of Tubes 1 to 5 at a 20 cm Pool Height During a Decreasing Heat Flux (DTB37)

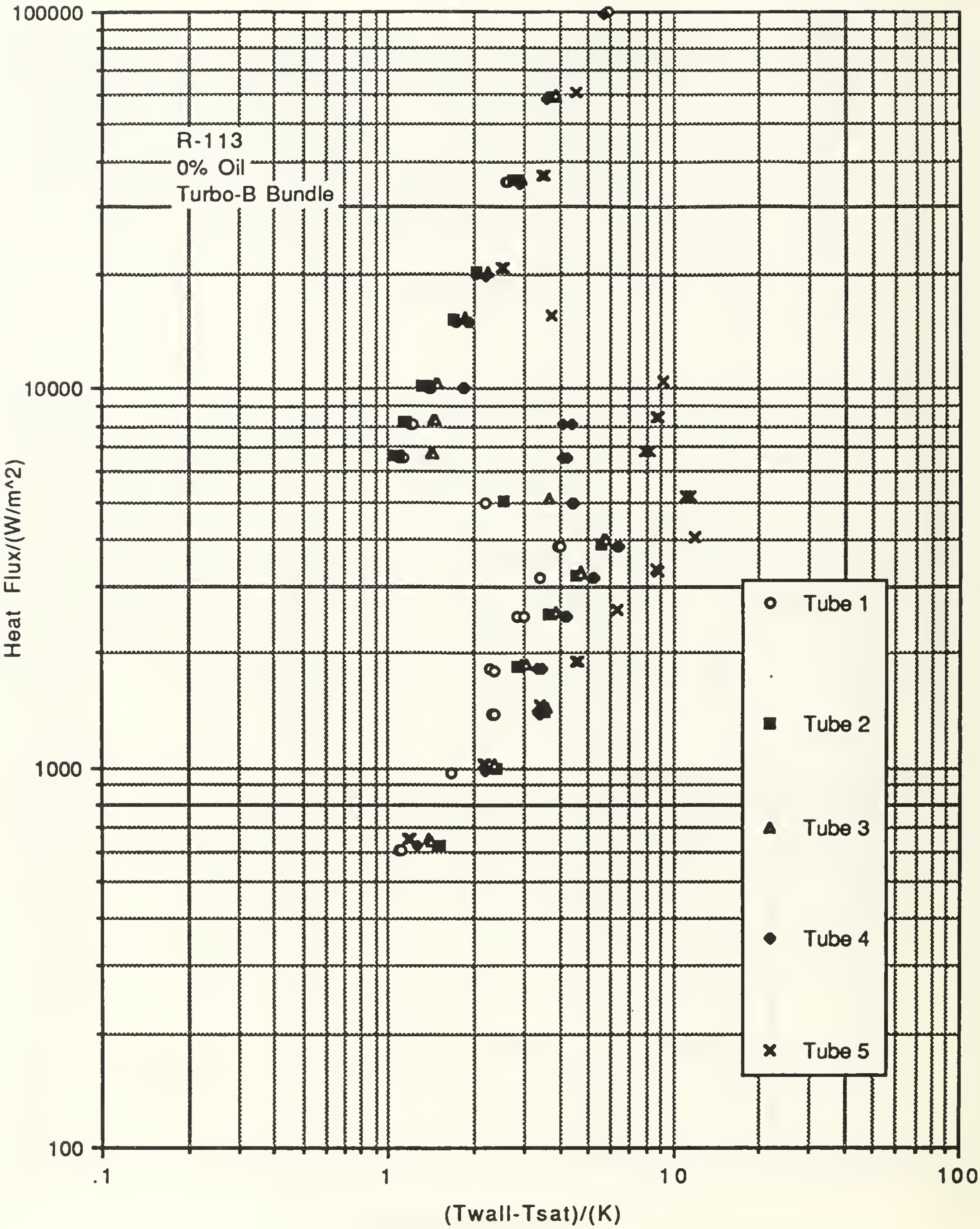

Figure 39. Performance Variation of the Bundle at a 20 cm Pool Height During a Increasing Heat Flux (ITB38)

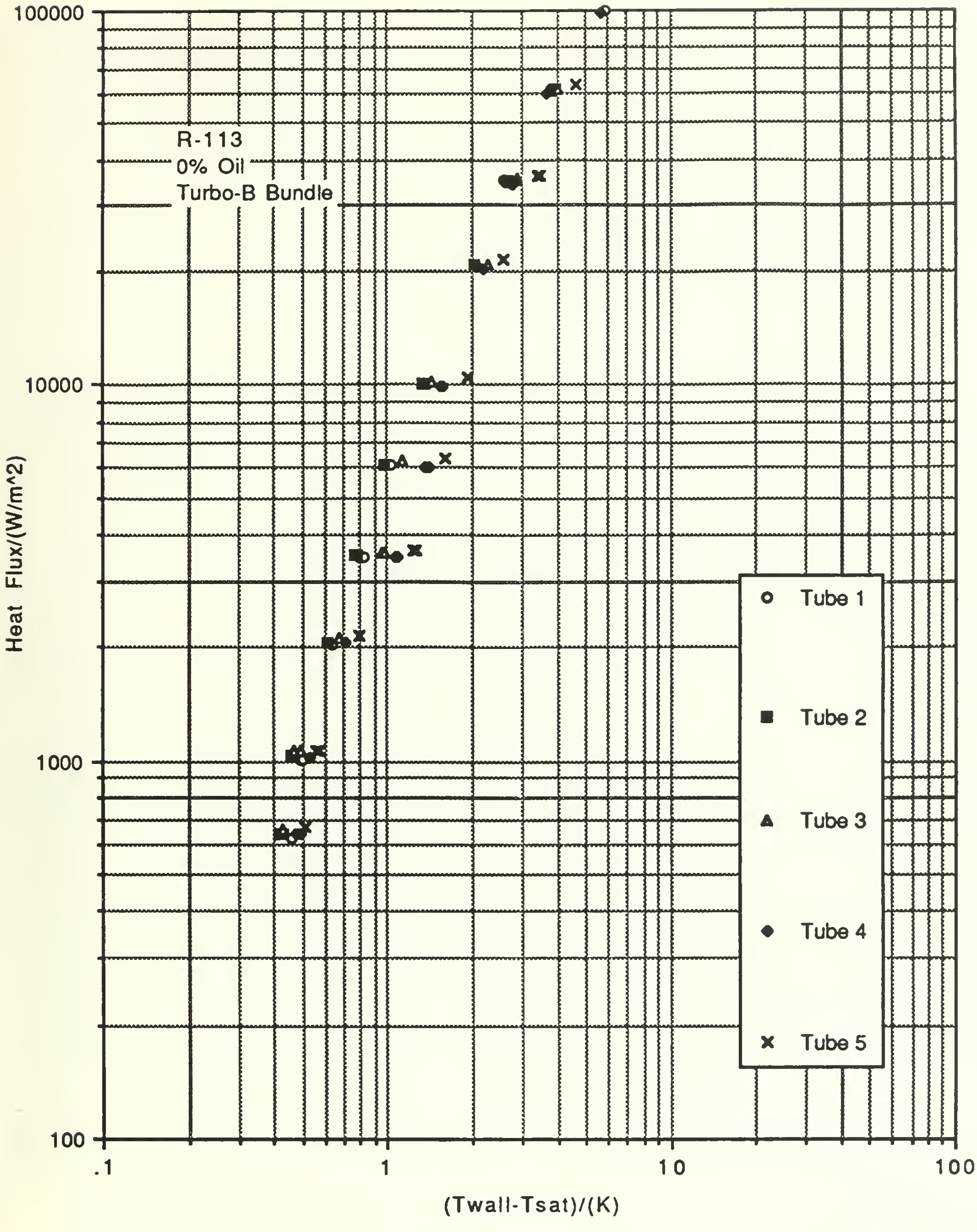

Figure 40. Performance Variation of the Bundle at a 20 cm Pool Height During a Decreasing Heat Flux (DTB38)

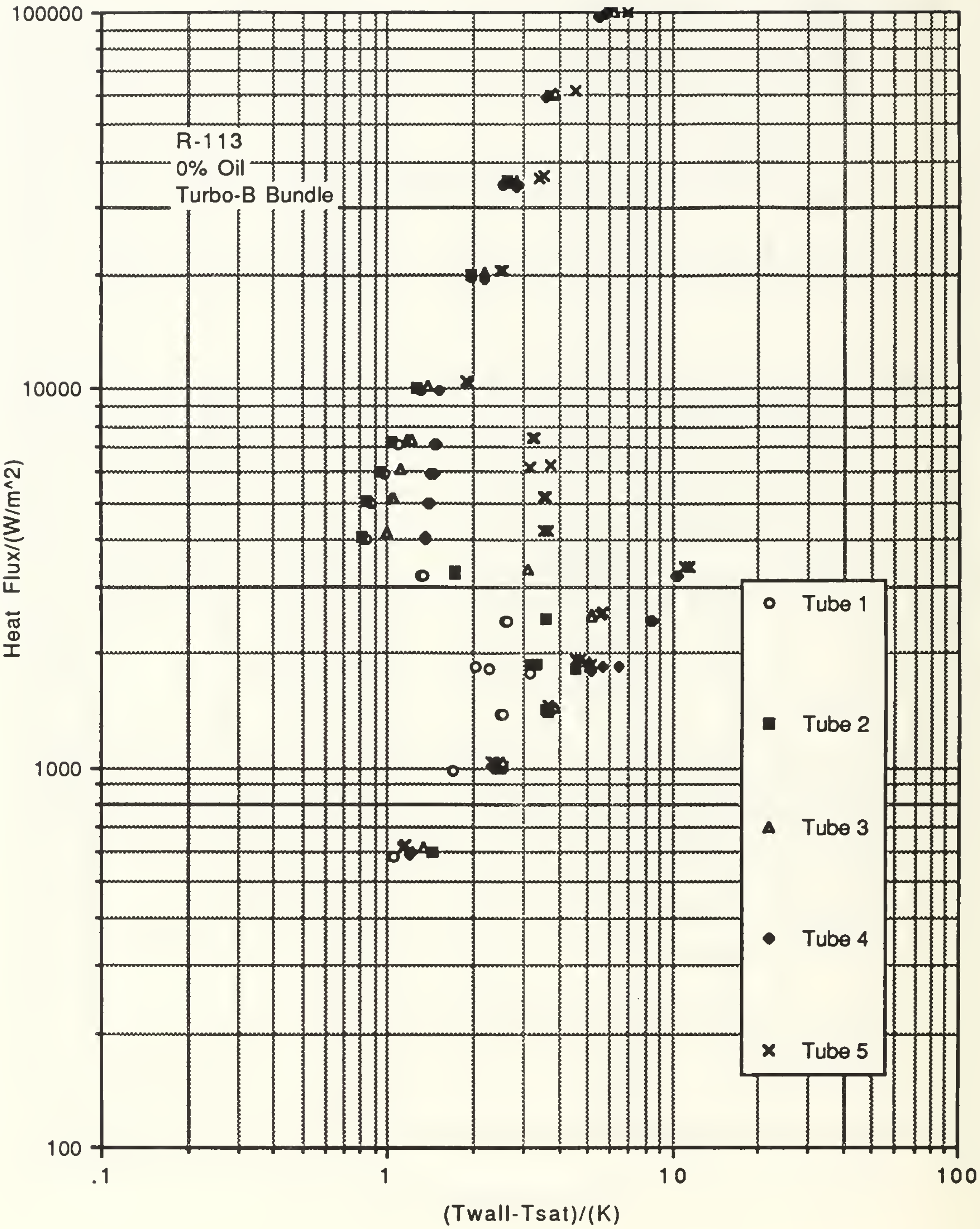

Figure 41. Performance Variation of the Bundle plus Simulation Heaters at a 20 cm Pool Height During a Increasing Heat Flux (ITB40)

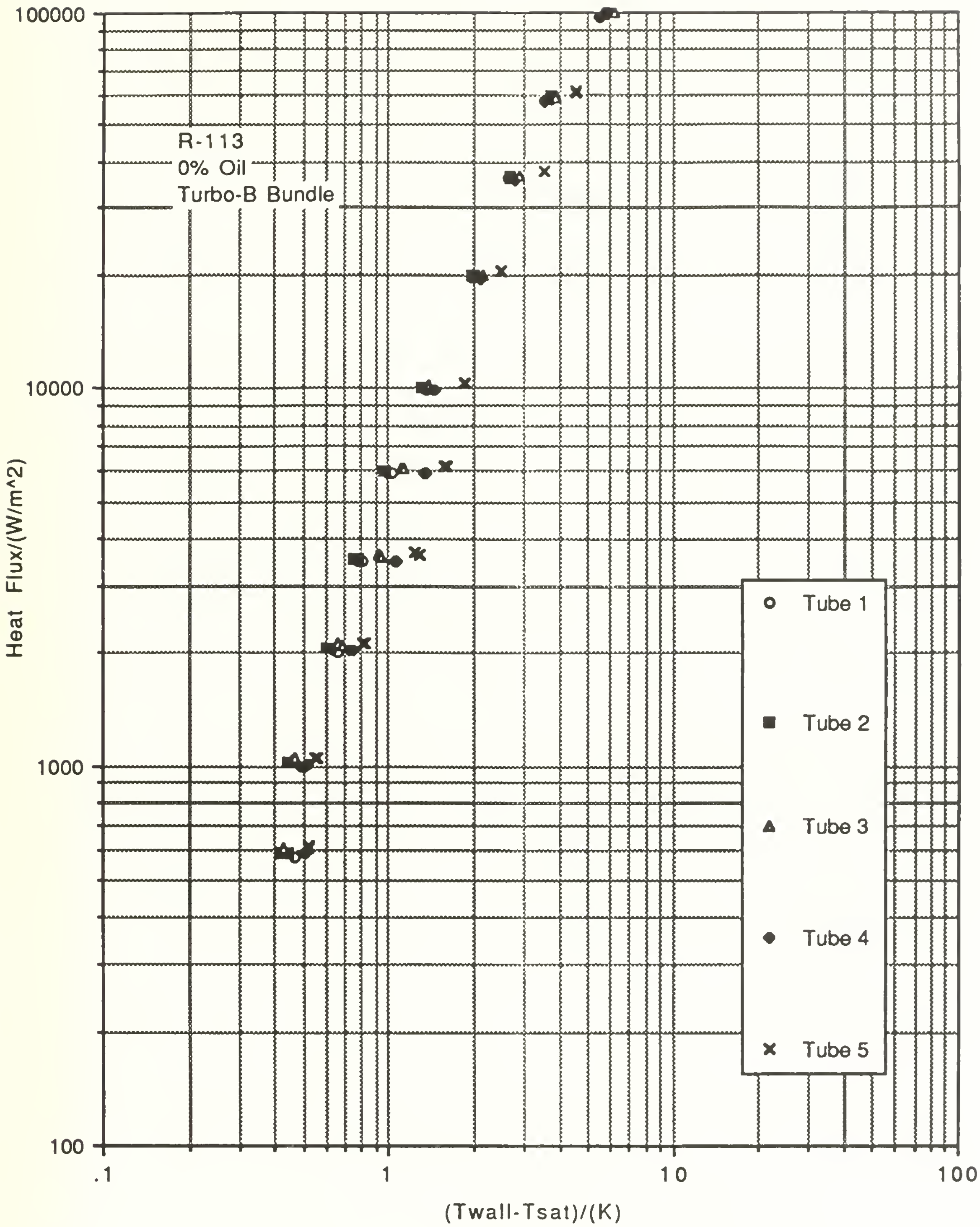

Figure 42. Performance Variation of the Bundle plus Simulation Heaters at a 20 cm Pool Height During a Decreasing Heat Flux (DTB40)

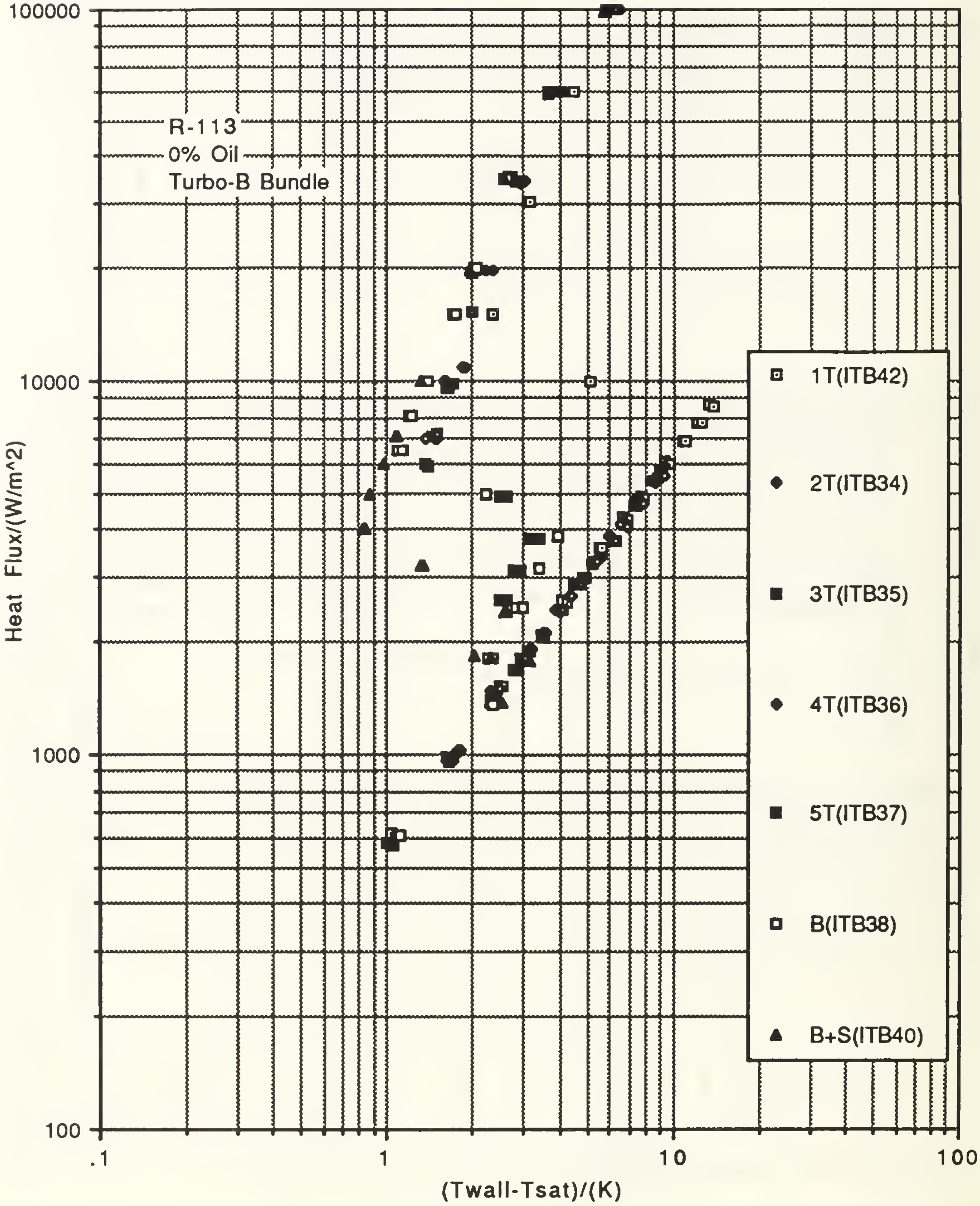

Figure 43. 20 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influenced by an Increasing Number of Heated Tubes in a Turbo-B Bundle During a Increasing Heat Flux

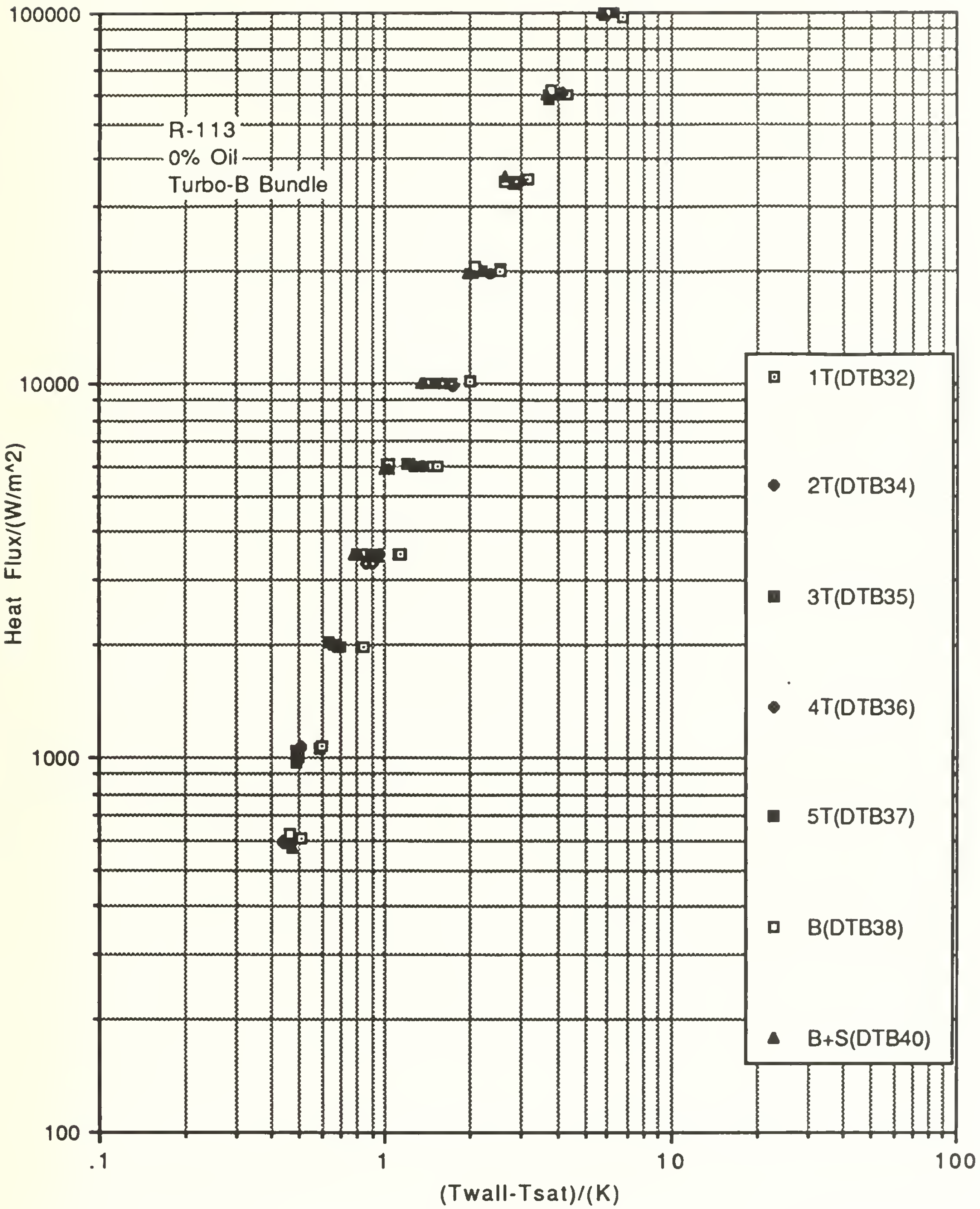

Figure 44. 20 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influenced by an Increasing Number of Heated Tubes in a Turbo-B Bundle During a Decreasing Heat Flux.

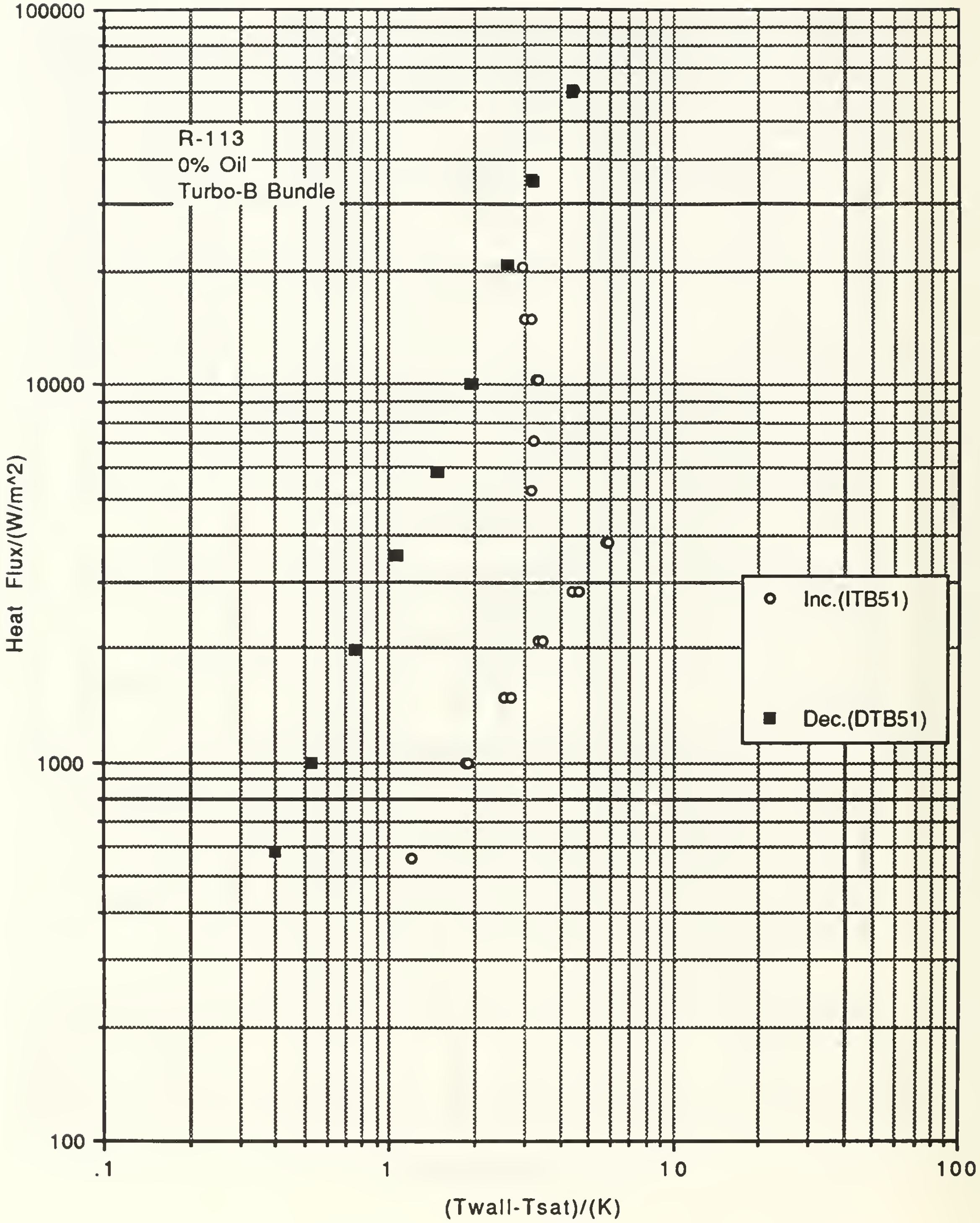

Figure 45. Performance of Tube 1 at a 0 cm Pool Height

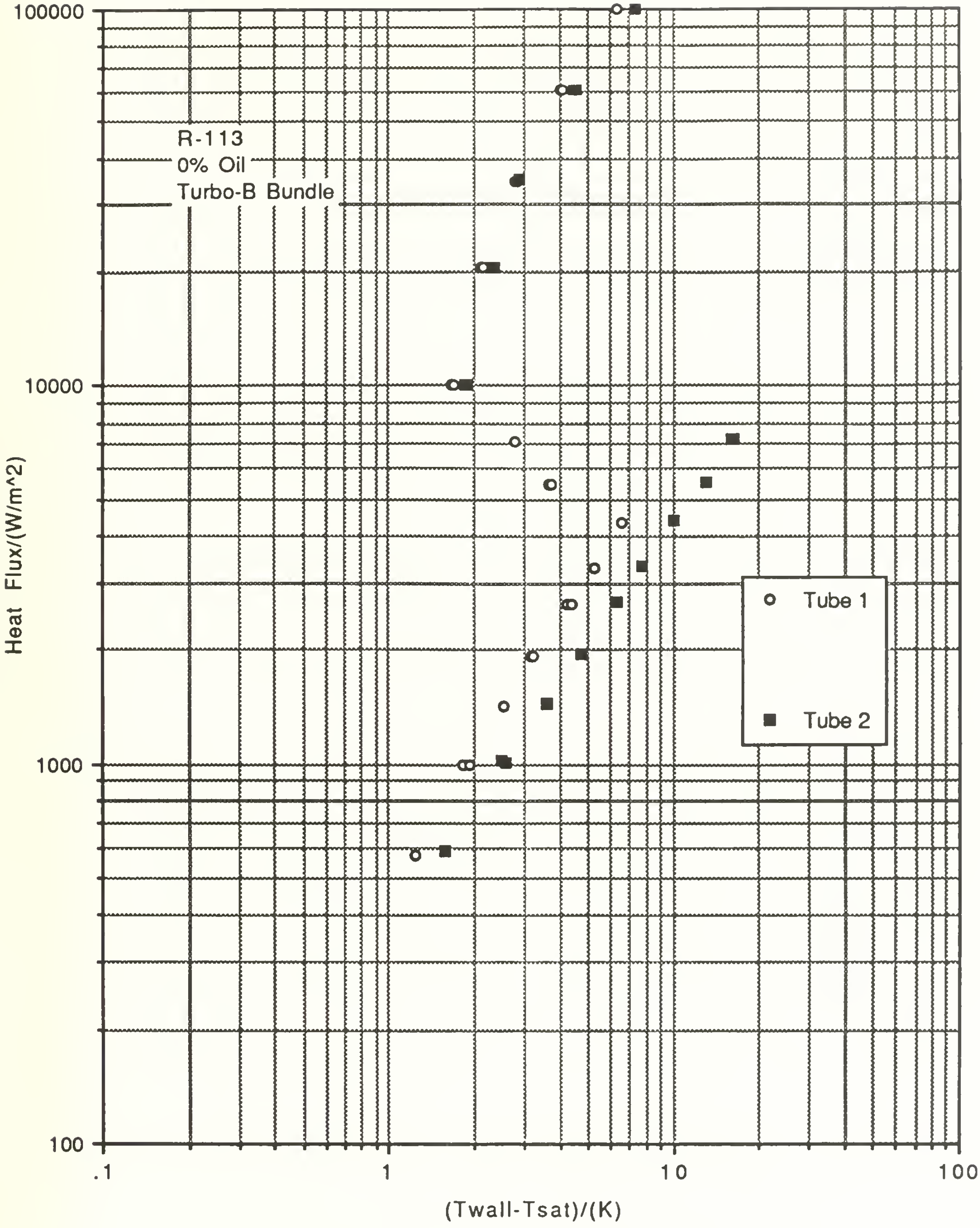

Figure 46. Performance Variation of Tubes 1&2 at a 0 cm Pool Height During a Increasing Heat Flux (ITB52)

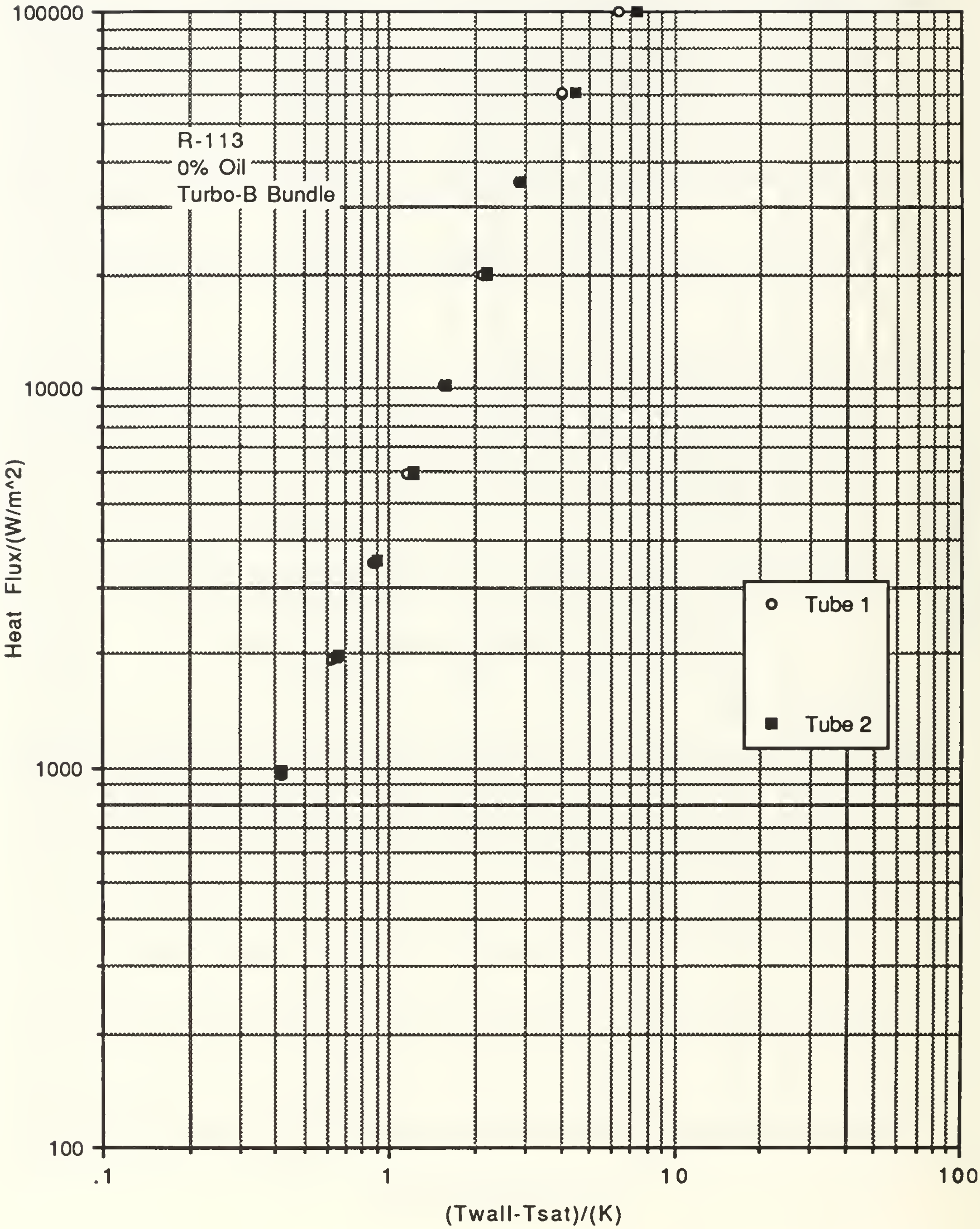

Figure 47. Performance Variation of Tubes 1&2 at a 0 cm Pool Height During a Decreasing Heat Flux (DTB52)

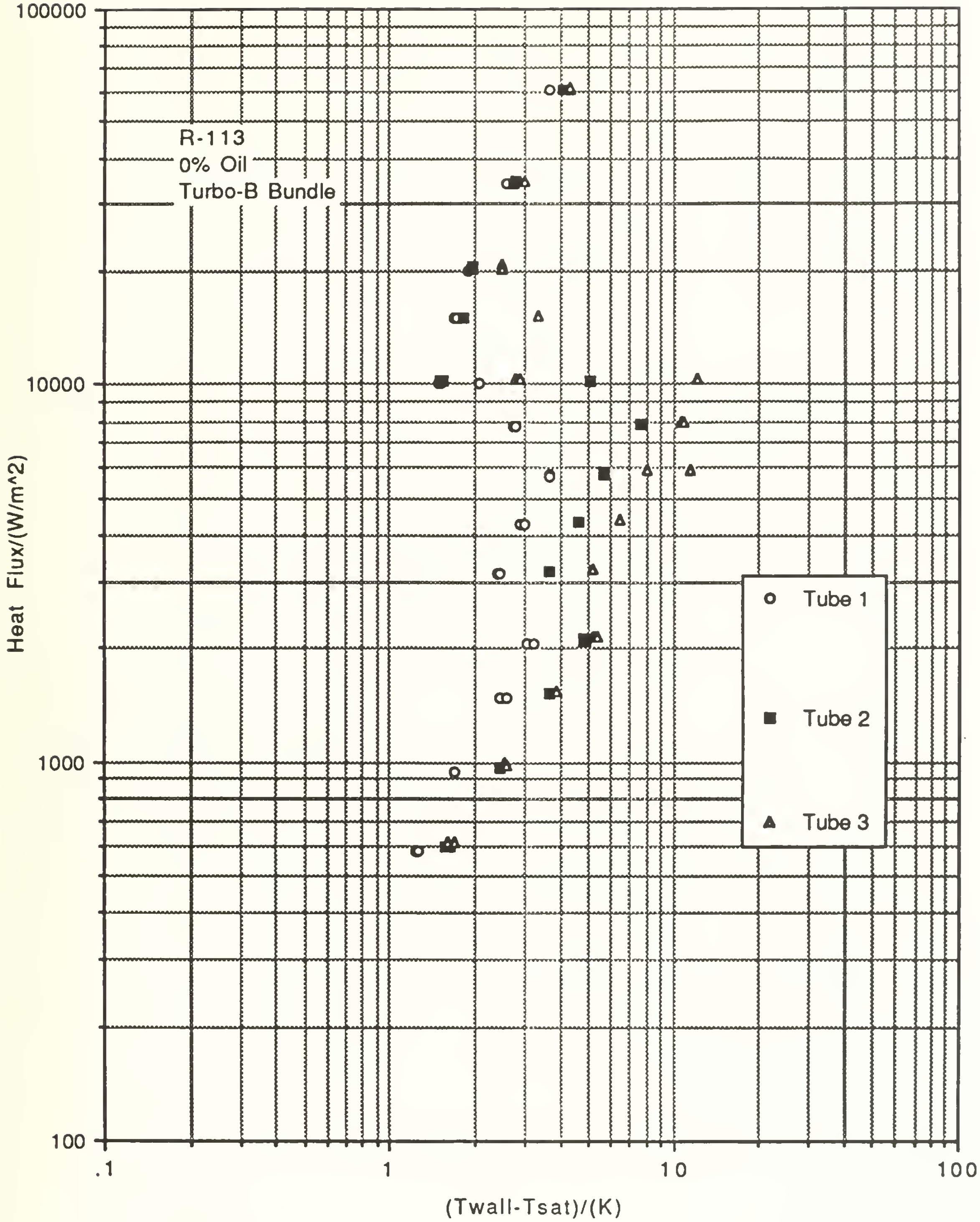

Figure 48. Performance Variation of Tubes 1 to 3 at a 0 cm Pool Height During a Increasing Heat Flux (ITB53)

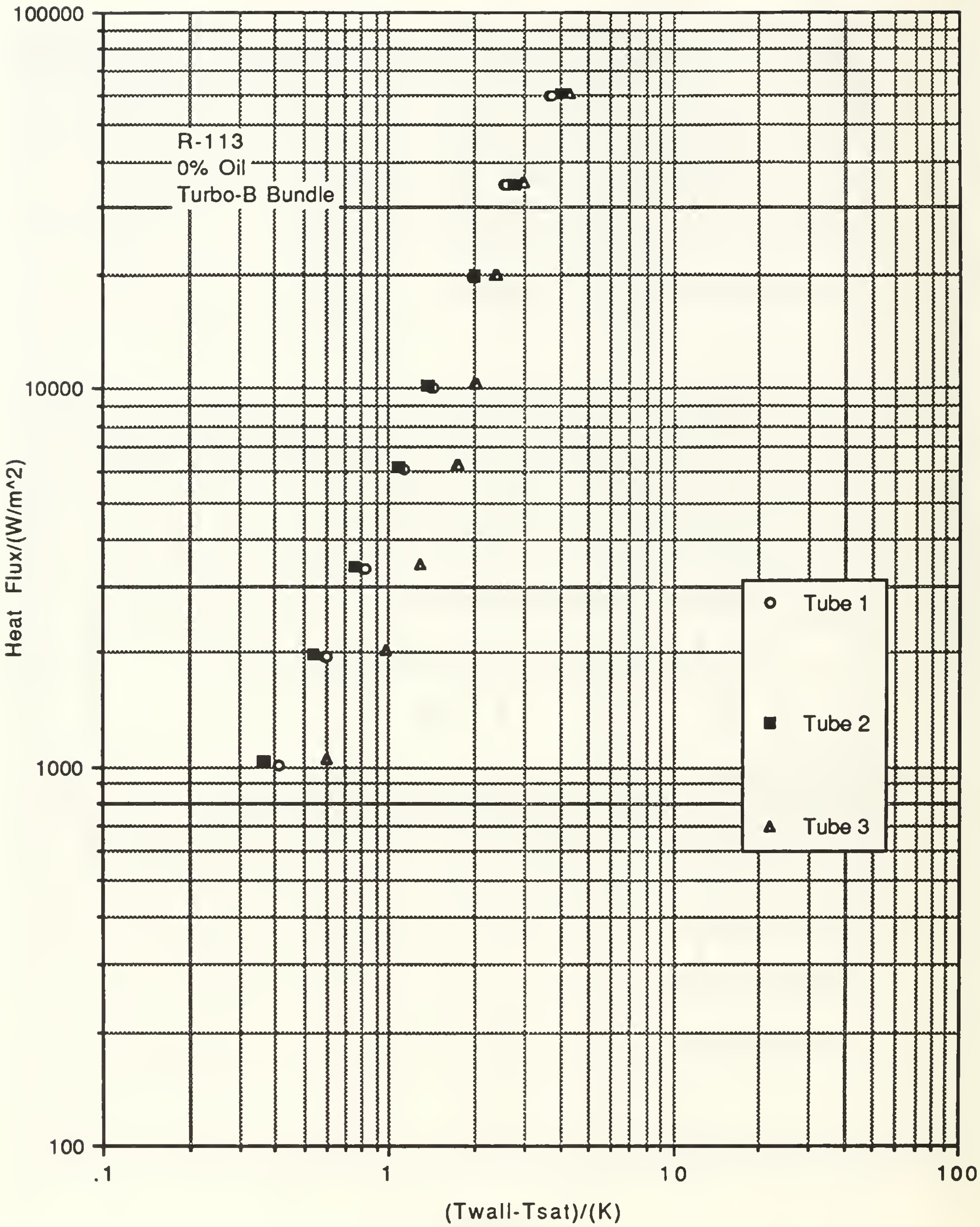

Figure 49. Performance Variation of Tubes 1 to 3 at a 0 cm Pool Height During a Decreasing Heat Flux (DTB53)

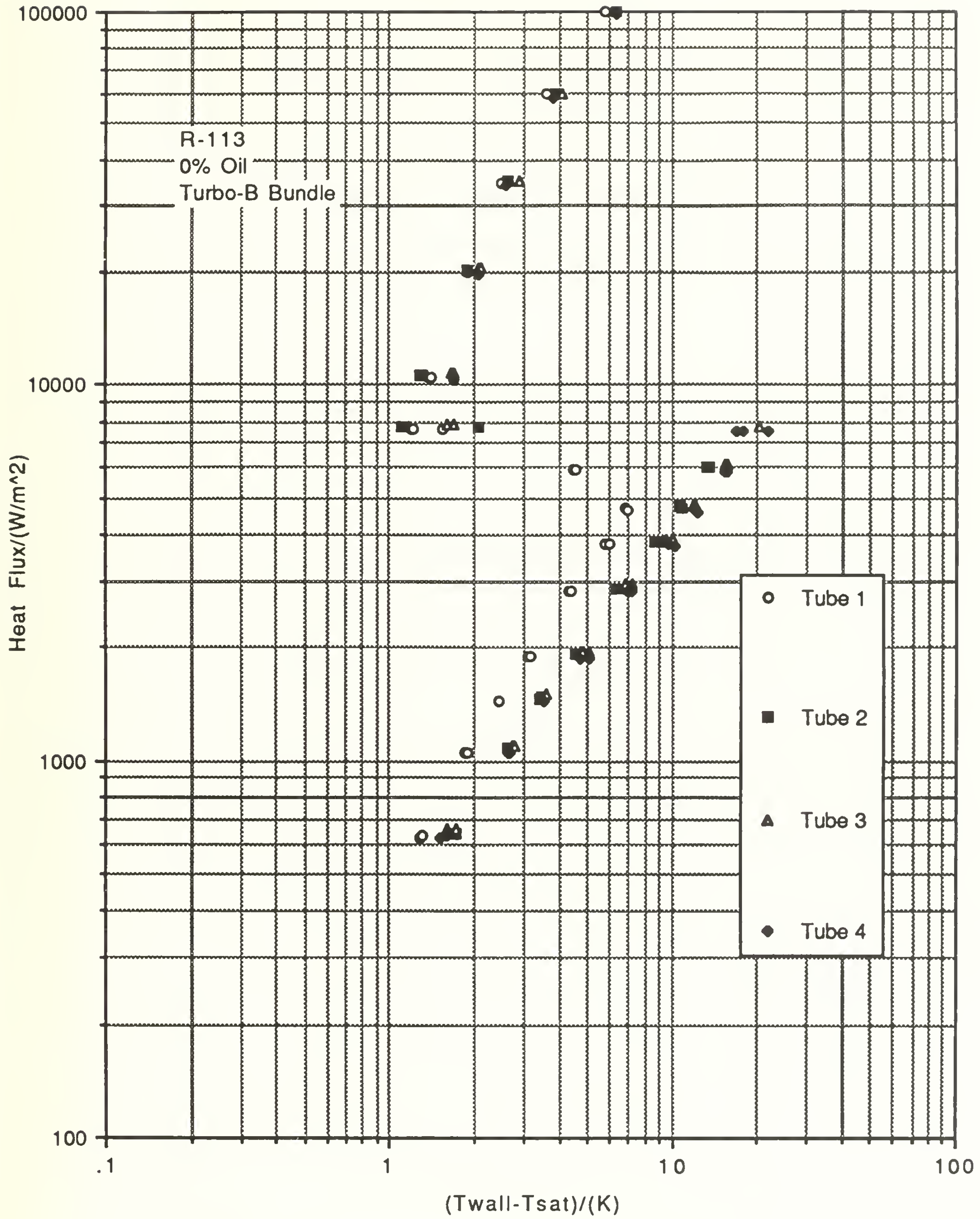

Figure 50. Performance Variation of Tubes 1 to 4 at a 0 cm Pool Height During a Increasing Heat Flux (ITB55)

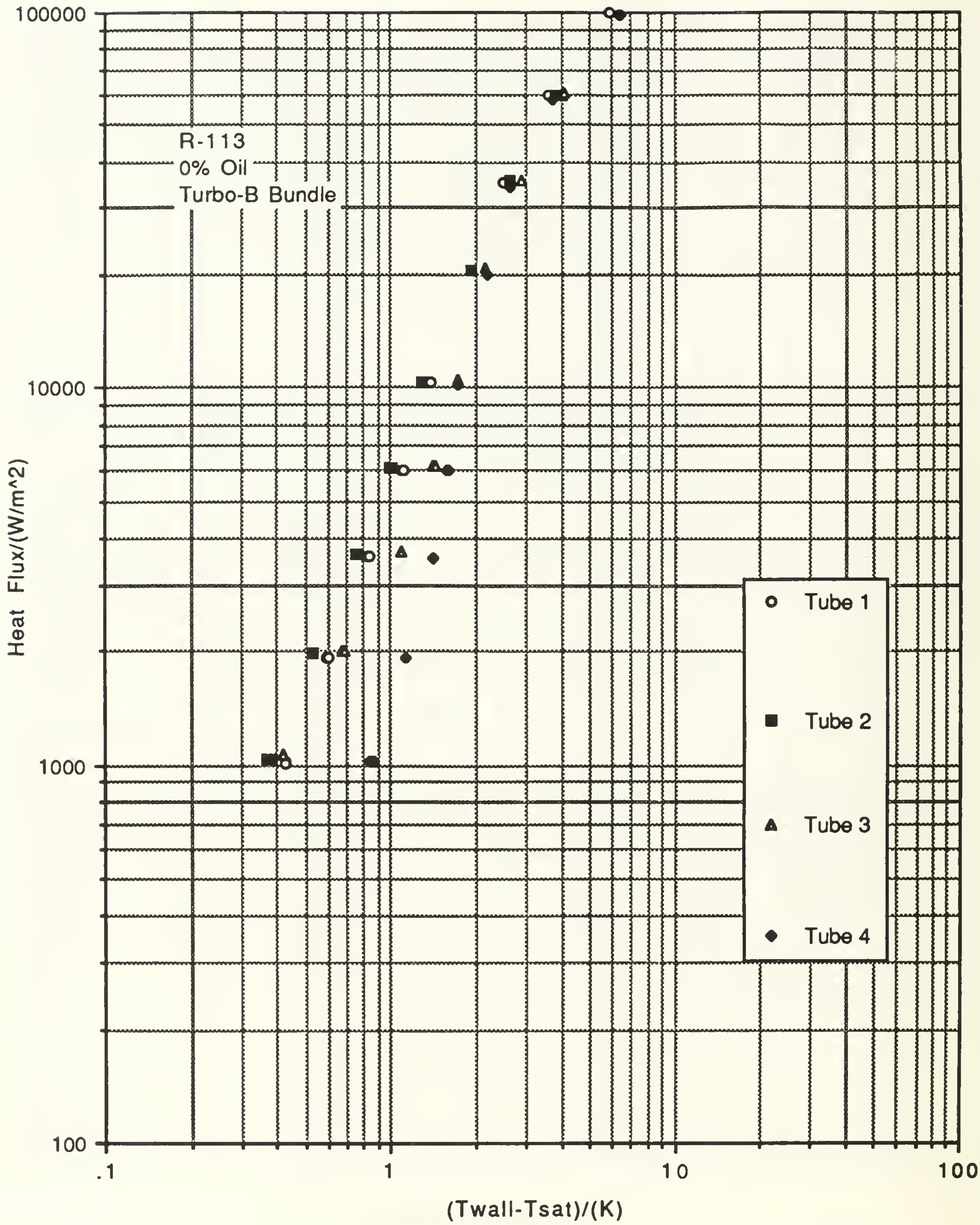

Figure 51. Performance Variation of Tubes 1 to 4 at a 0 cm Pool Height During a Decreasing Heat Flux (DTB55)

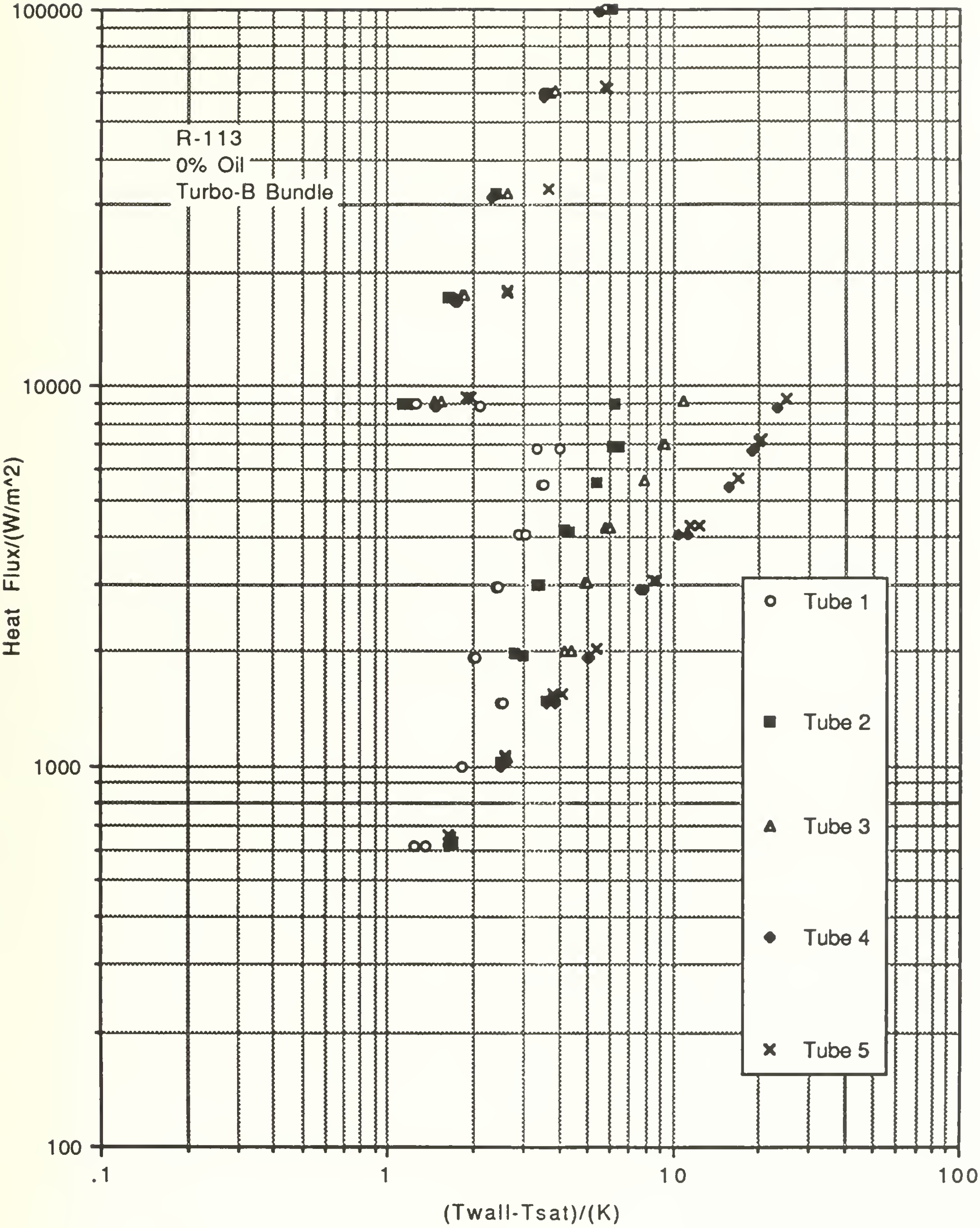

Figure 52. Performance Variation of Tubes 1 to 5 at a 0 cm Pool Height During a Increasing Heat Flux (ITB56)

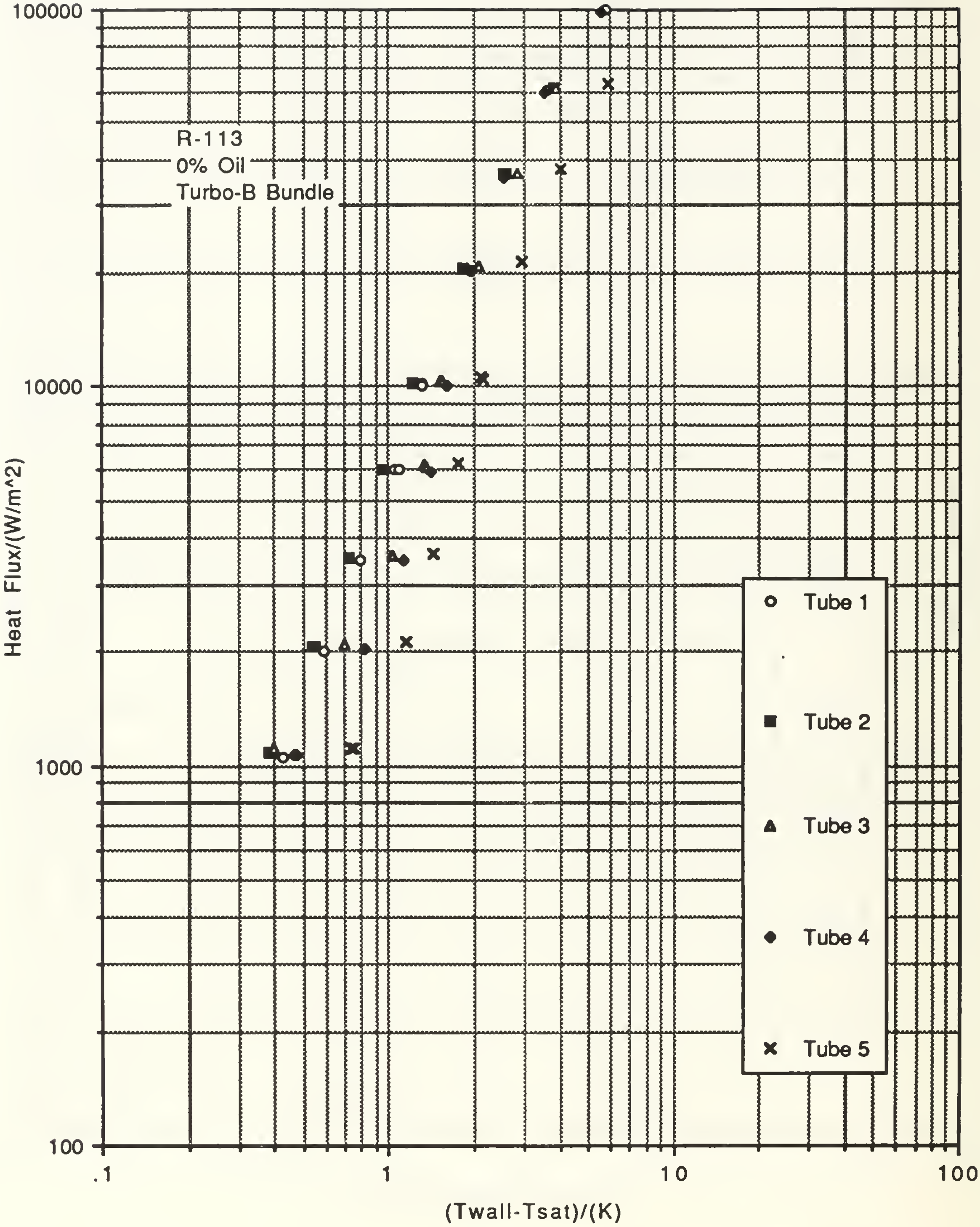

Figure 53. Performance Variation of Tubes 1 to 5 at a 0 cm Pool Height During a Decreasing Heat Flux (DTB56)

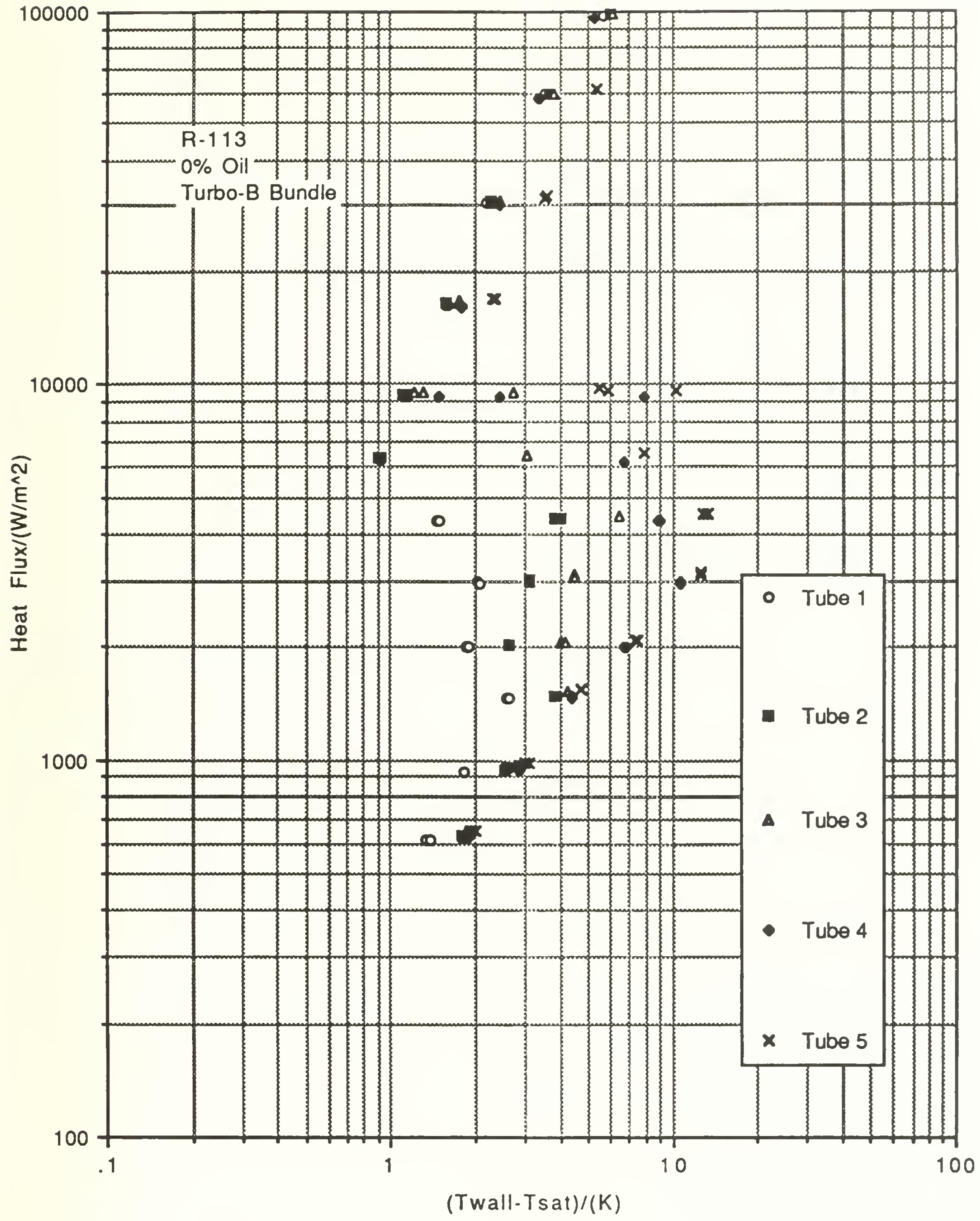

Figure 54. Performance Variation of the Bundle at a 0 cm Pool Height During a Increasing Heat Flux (ITB57)

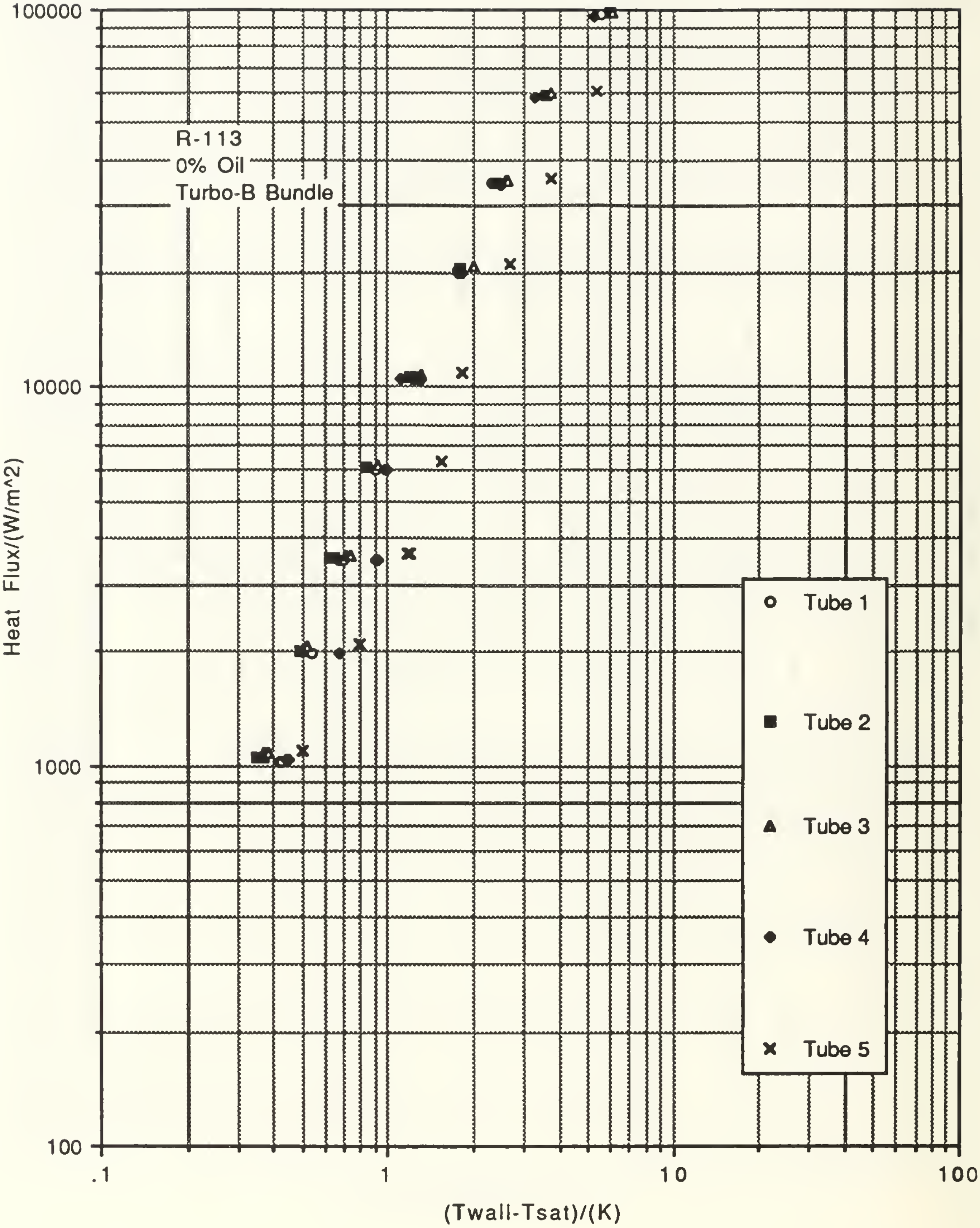

Figure 55. Performance Variation of the Bundle at a 0 cm Pool Height During a Decreasing Heat Flux (DTB57)

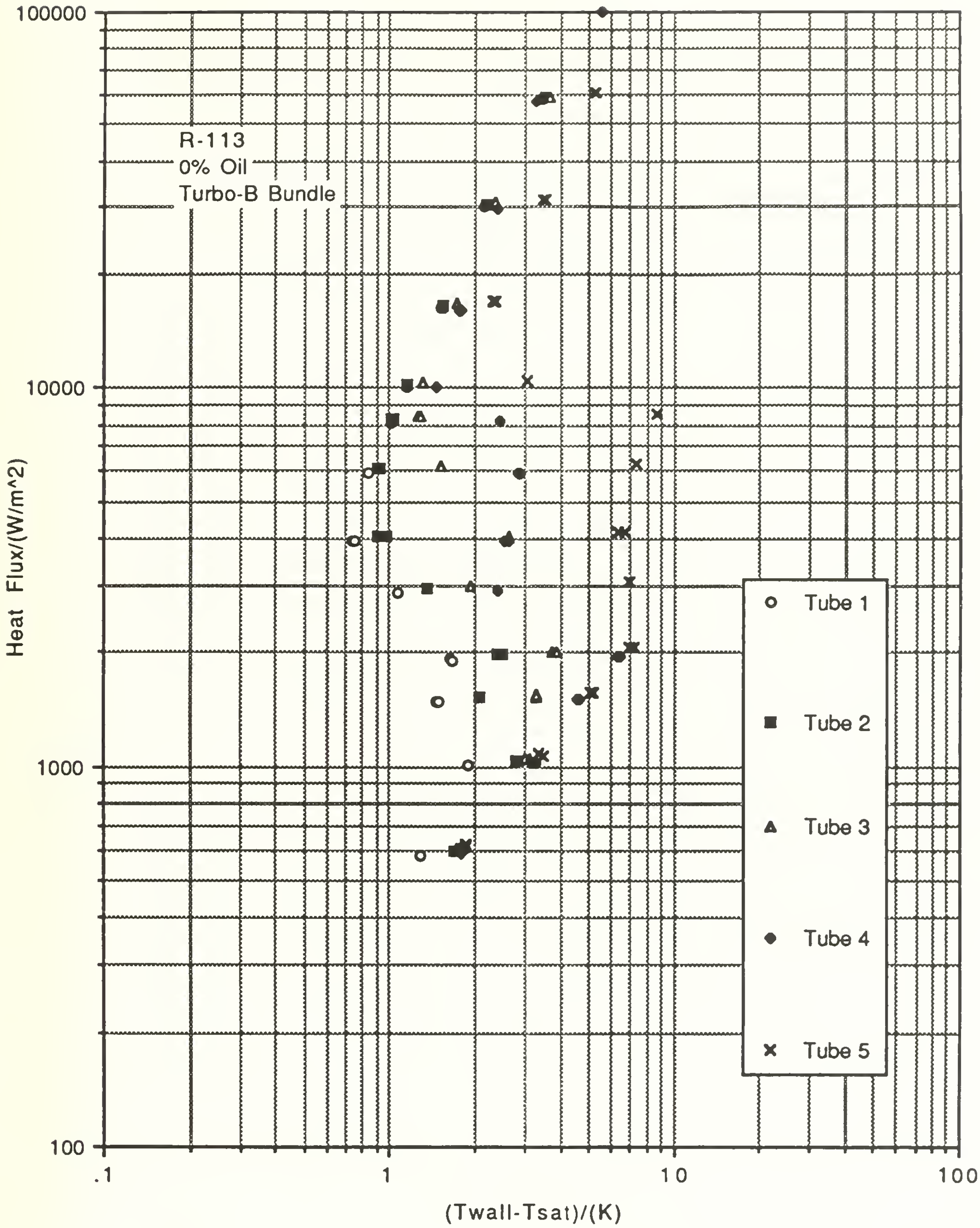

Figure 56. Performance Variation of the Bundle plus Simulation Heaters at a 0 cm Pool Height During a Increasing Heat Flux (ITB58)

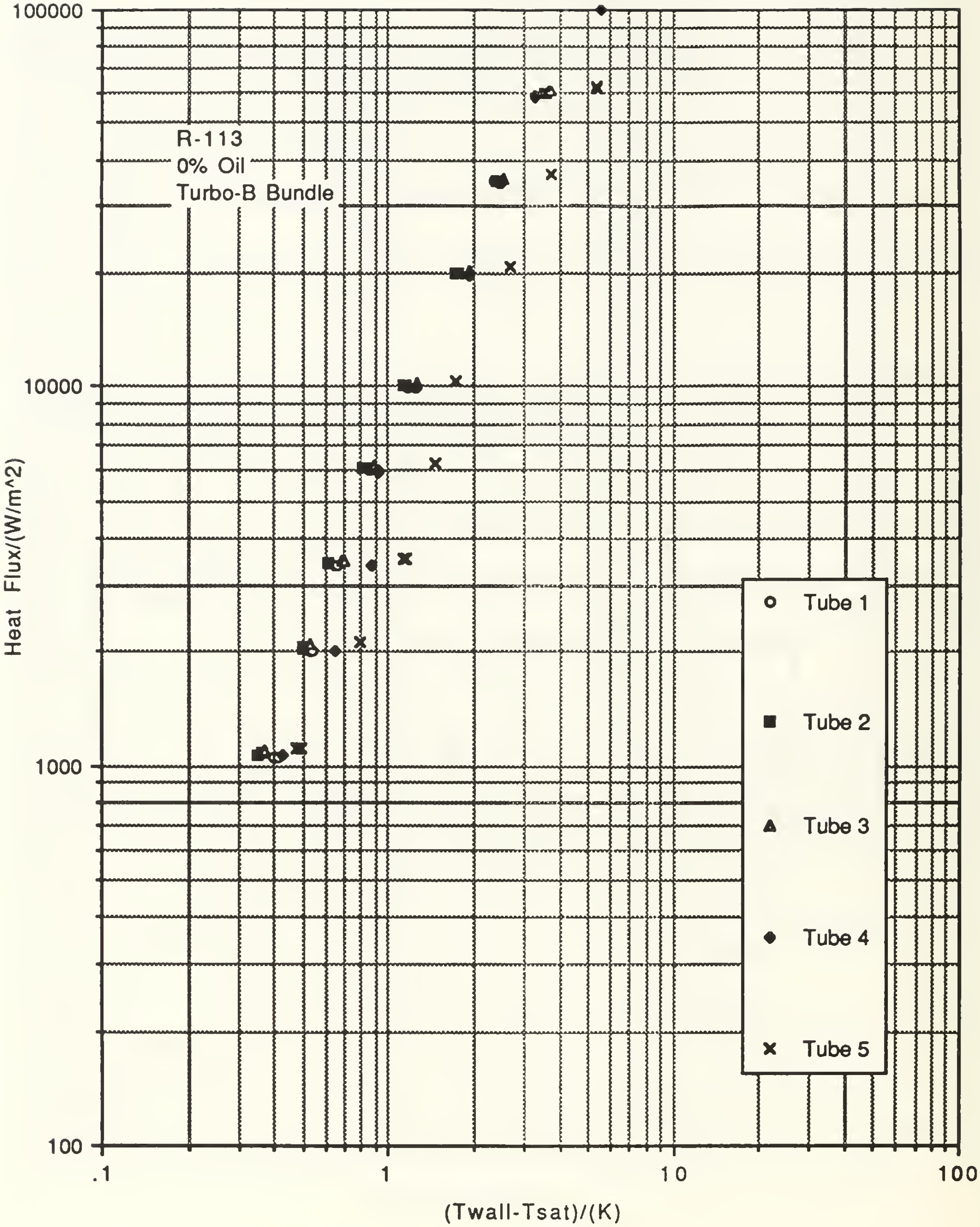

Figure 57. Performance Variation of the Bundle plus Simulation Heaters at a 0 cm Pool Height During a Decreasing Heat Flux (DTB58)

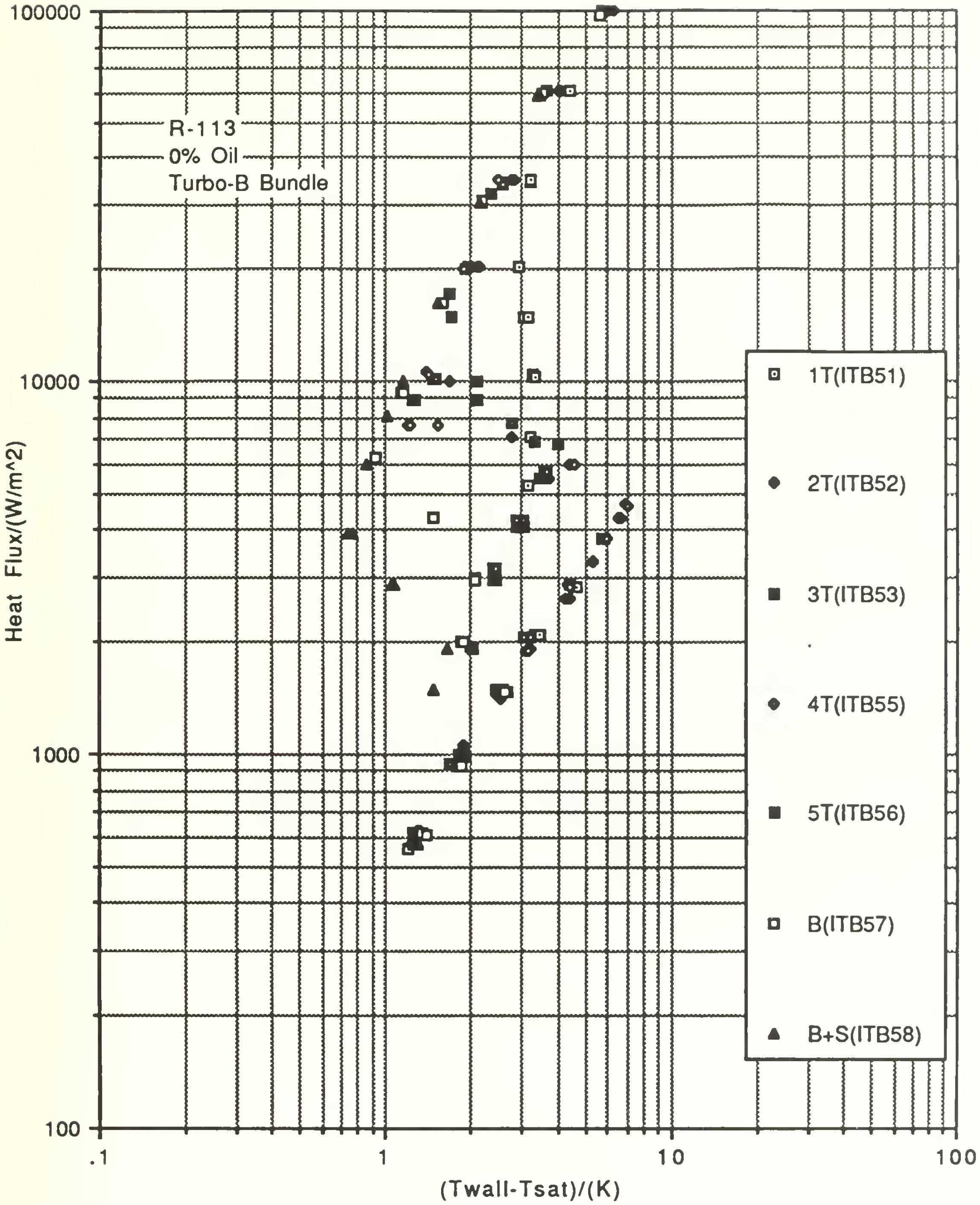

Figure 58. 0 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influenced by an Increasing Number of Heated Tubes in a Turbo-B Bundle During a Increasing Heat Flux

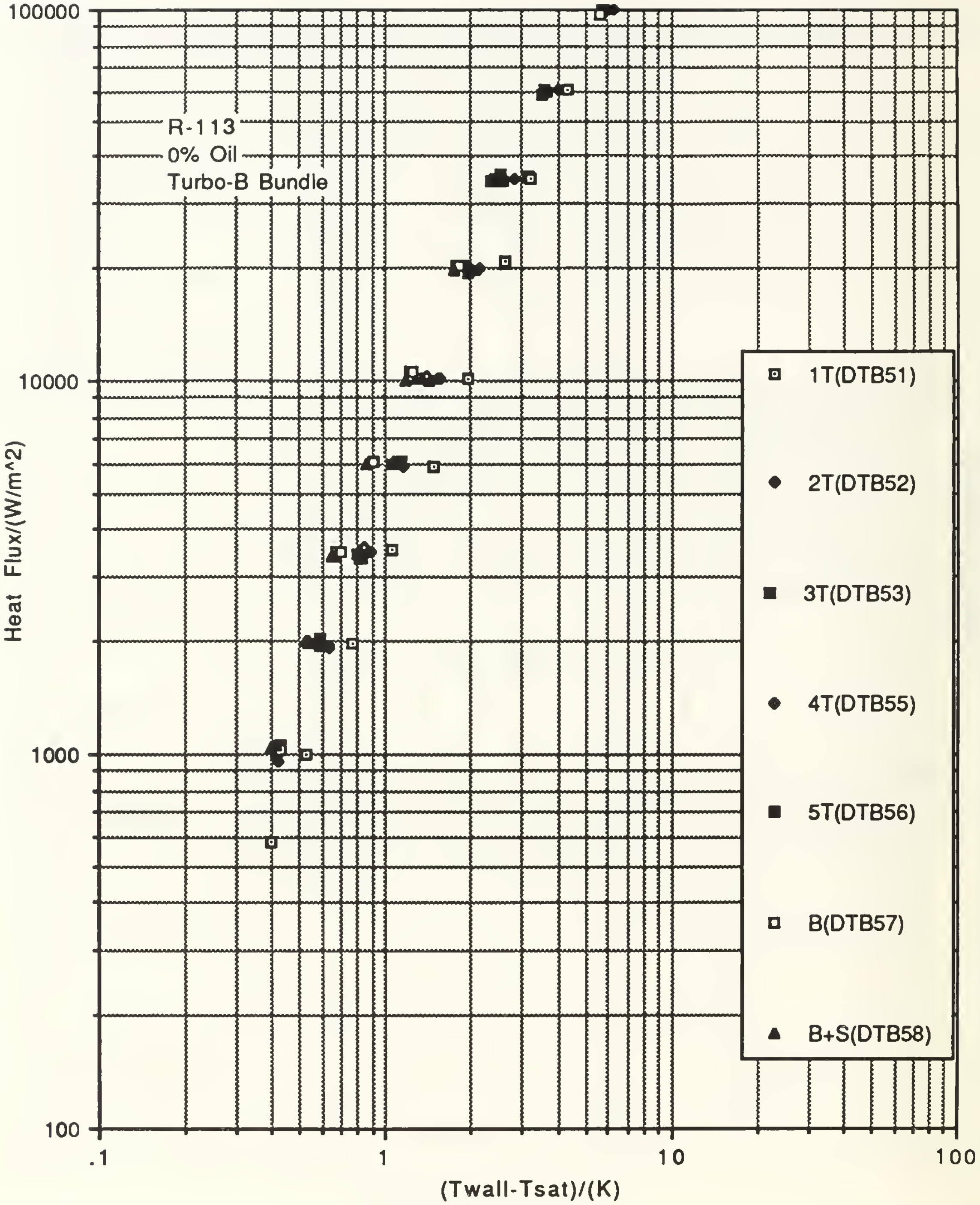

Figure 59. 0 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influenced by an Increasing Number of Heated Tubes in a Turbo-B Bundle During a Decreasing Heat Flux

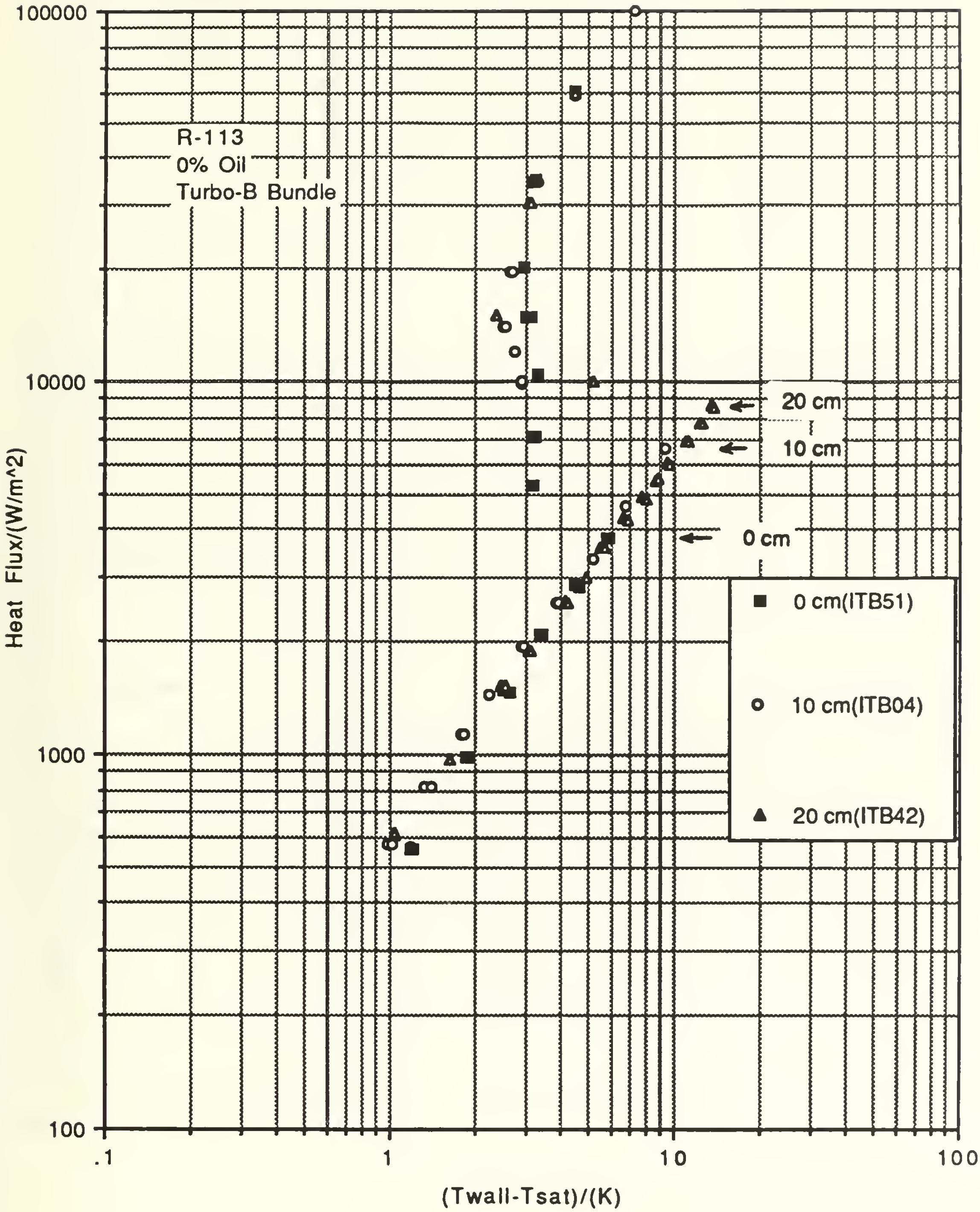

Figure 60. Comparison of Tube 1 in a Pool of R-113 for Three Different Pool Heights During a Increasing Heat Flux

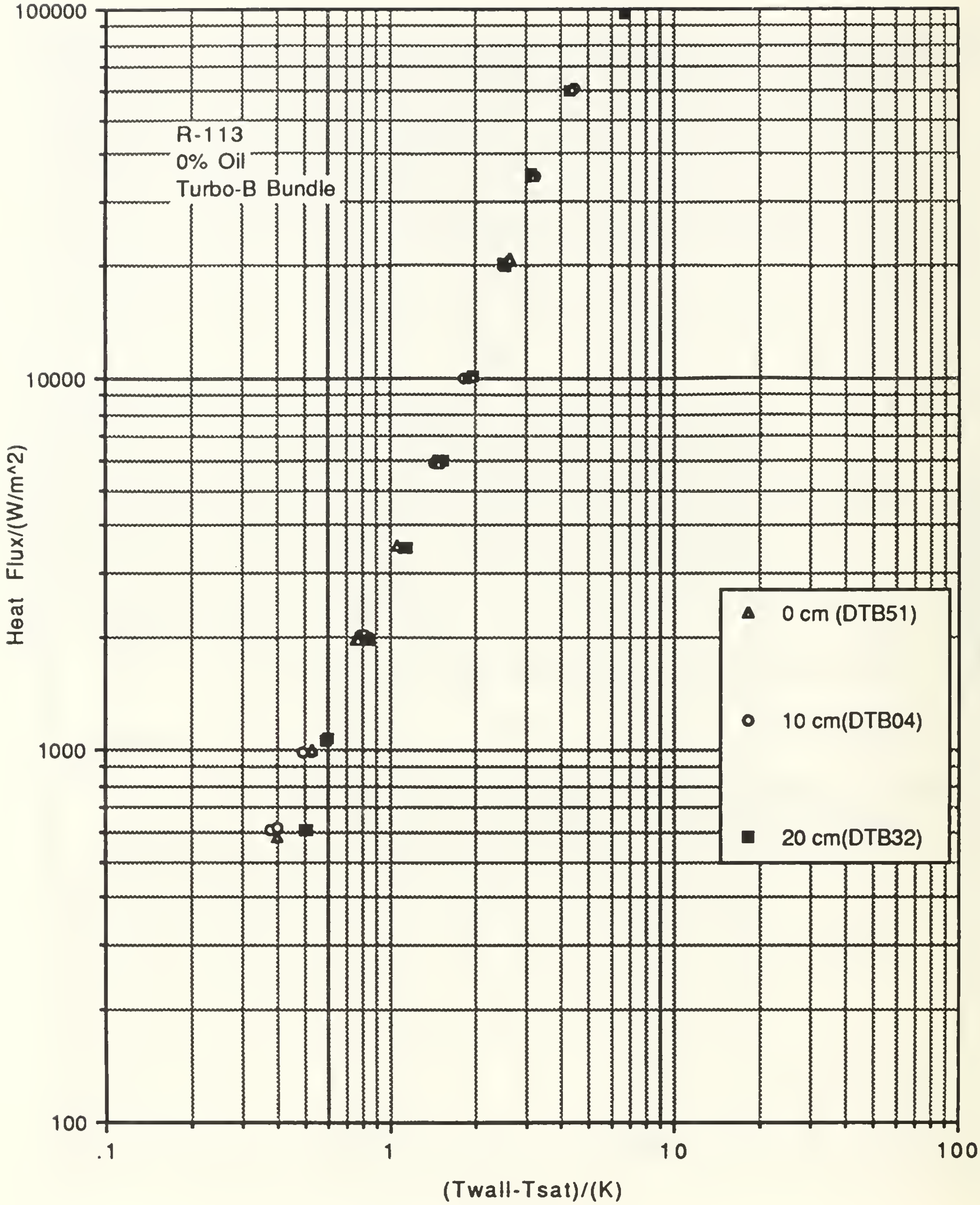

Figure 61. Comparison of Tube 1 in a Pool of R-113 for Three Different Pool Heights During a Decreasing Heat Flux

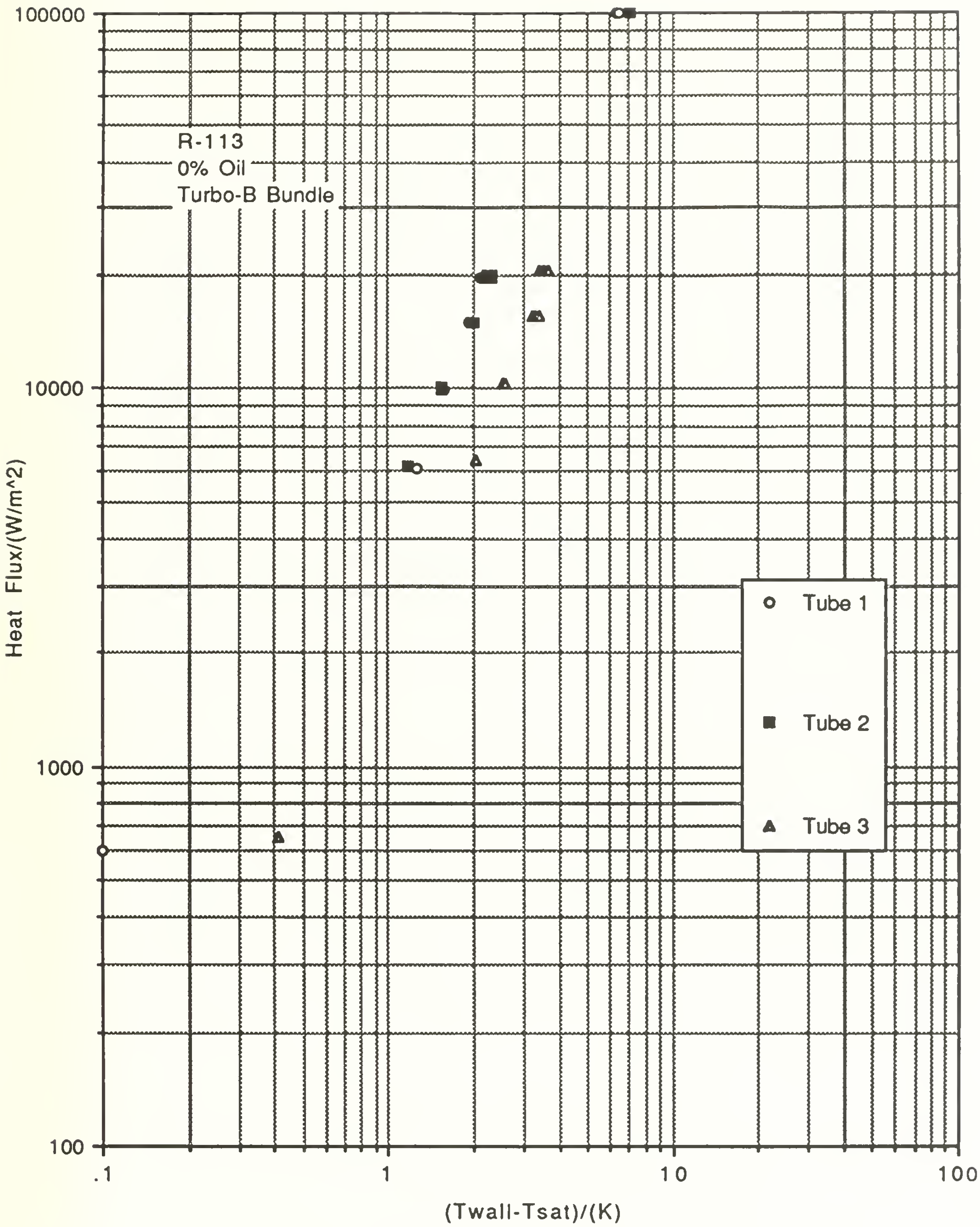

Figure 62. Performance Variation of Tubes 1 to 3 at a 10 cm Pool Height During a Decreasing Heat Flux with Auxiliary Heaters off (DTB06T)

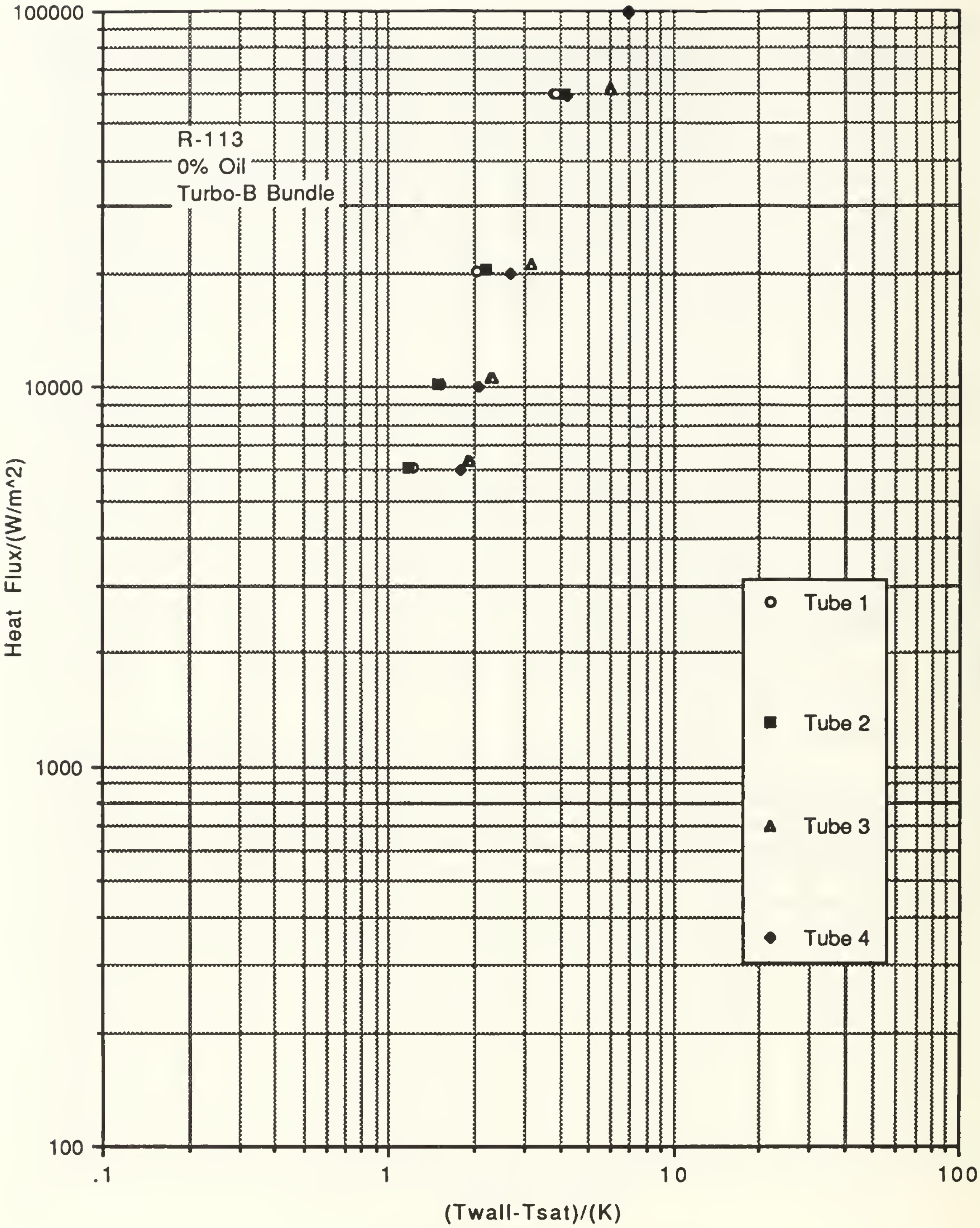

Figure 63. Performance Variation of Tubes 1 to 4 at a 10 cm Pool Height During a Decreasing Heat Flux with Auxiliary Heaters off (DTB07T)

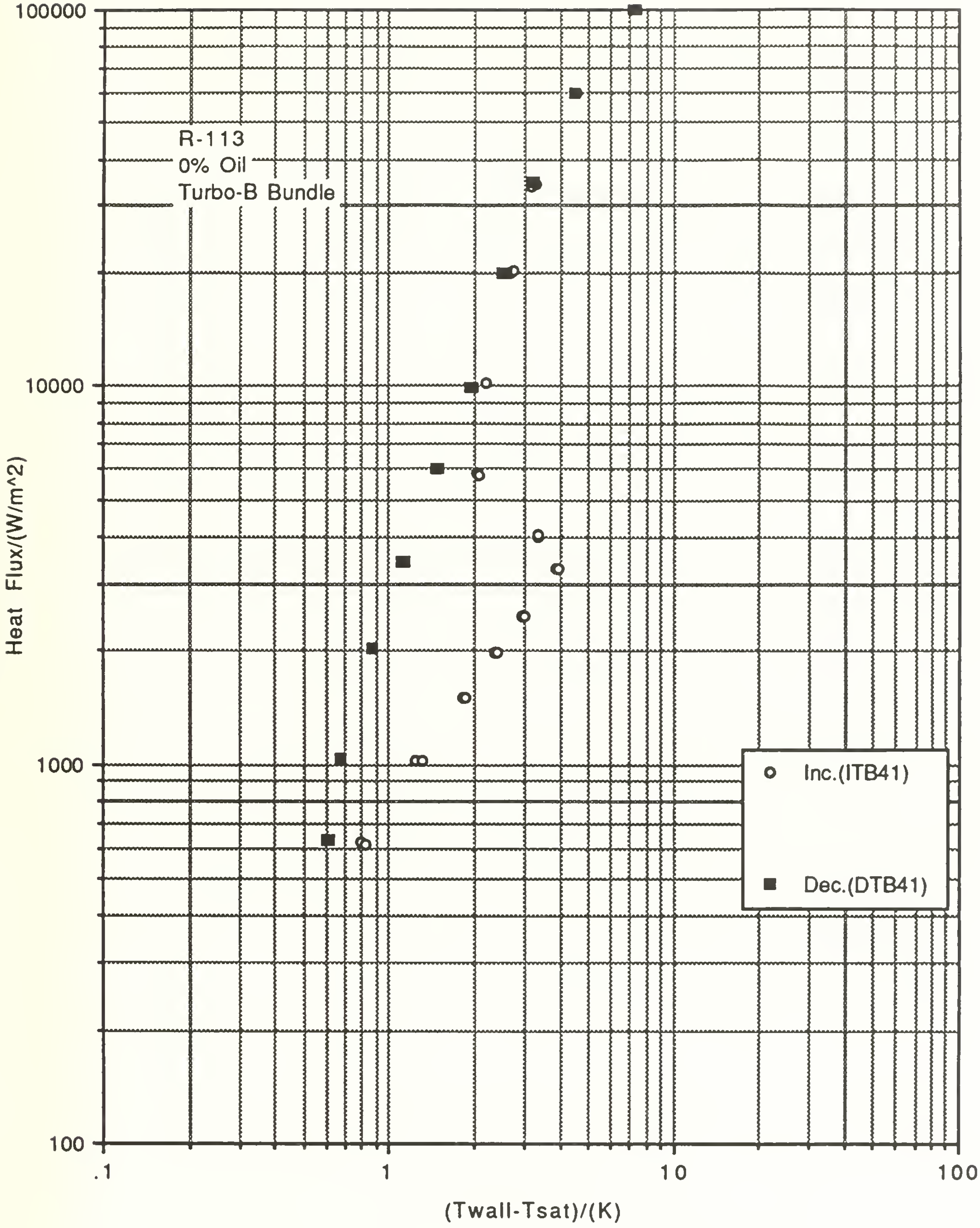

Figure 64. Performance of Tube 1 at a 20 cm Pool Height with the Auxiliary Heater Setting at 3kW

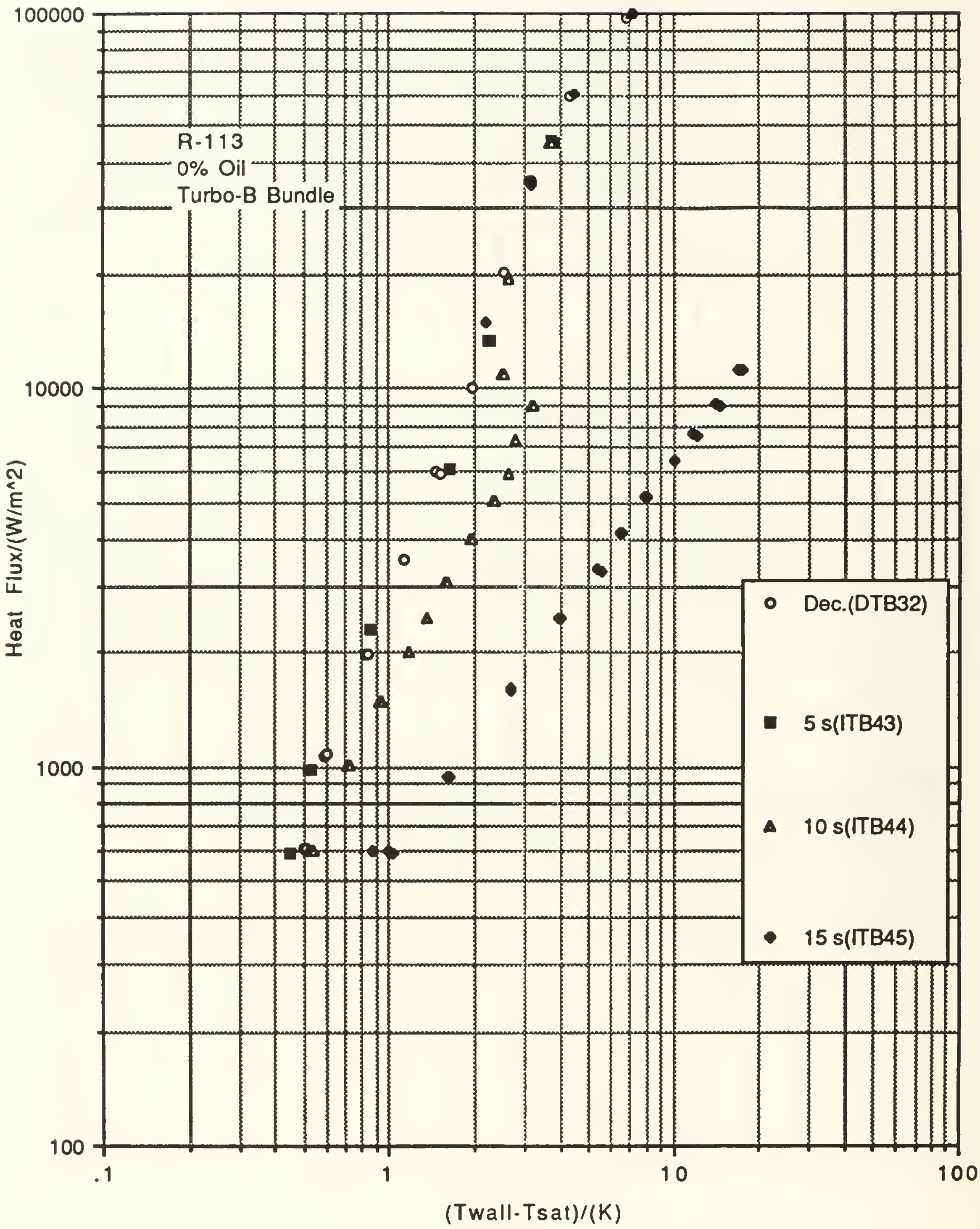

Figure 65. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 20 cm Pool Height

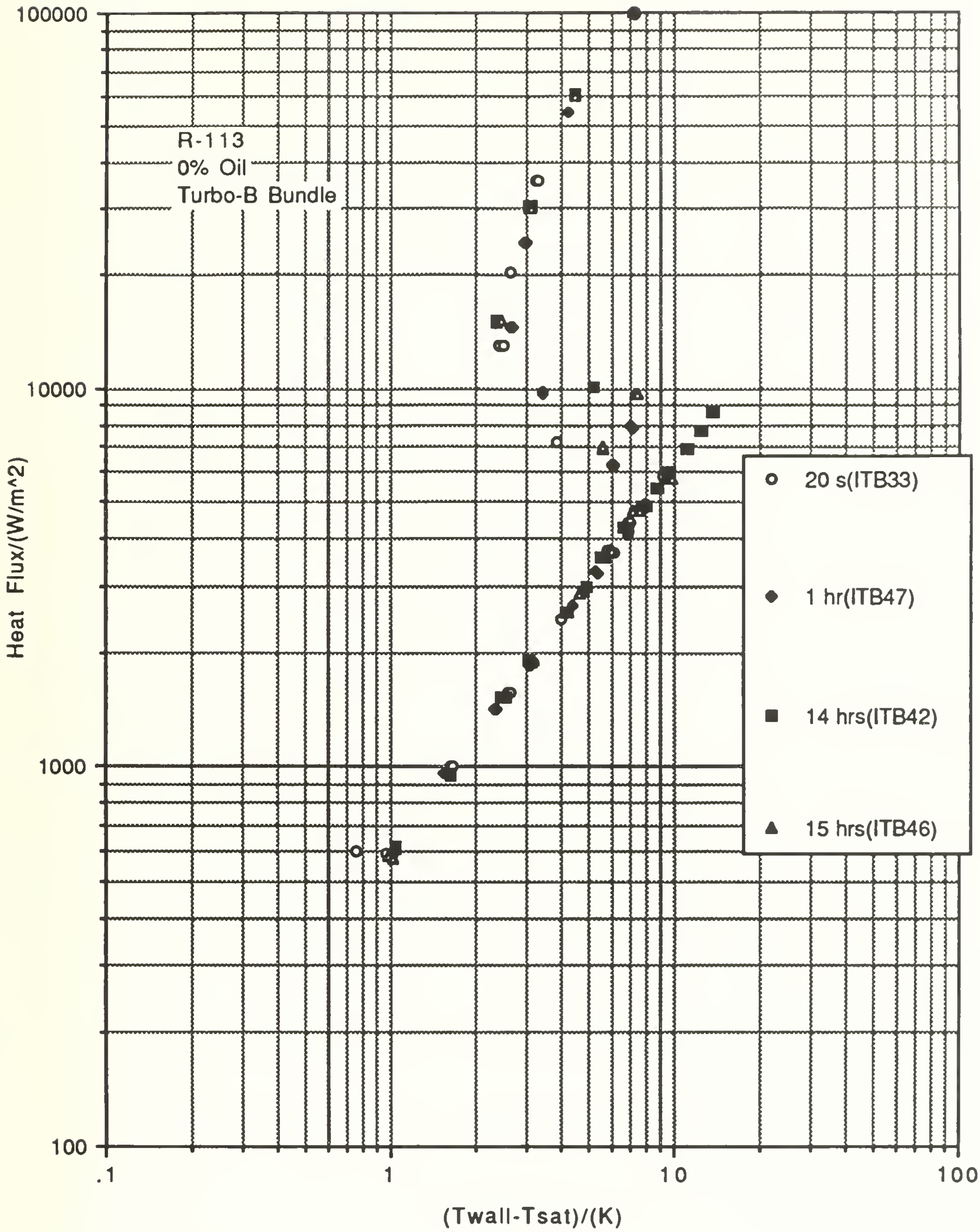

Figure 66. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 20 cm Pool Height

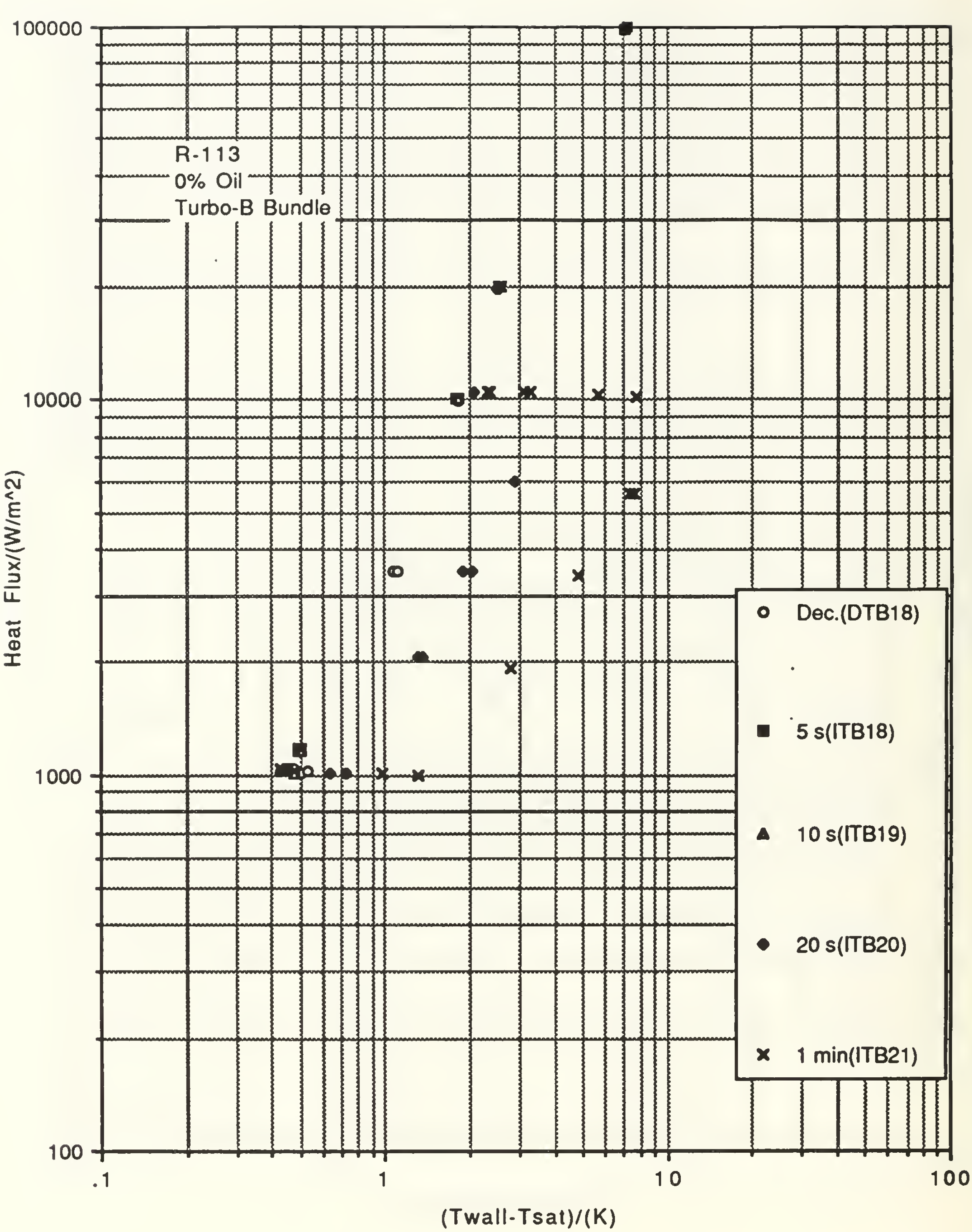

Figure 67. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 10 cm Pool Height

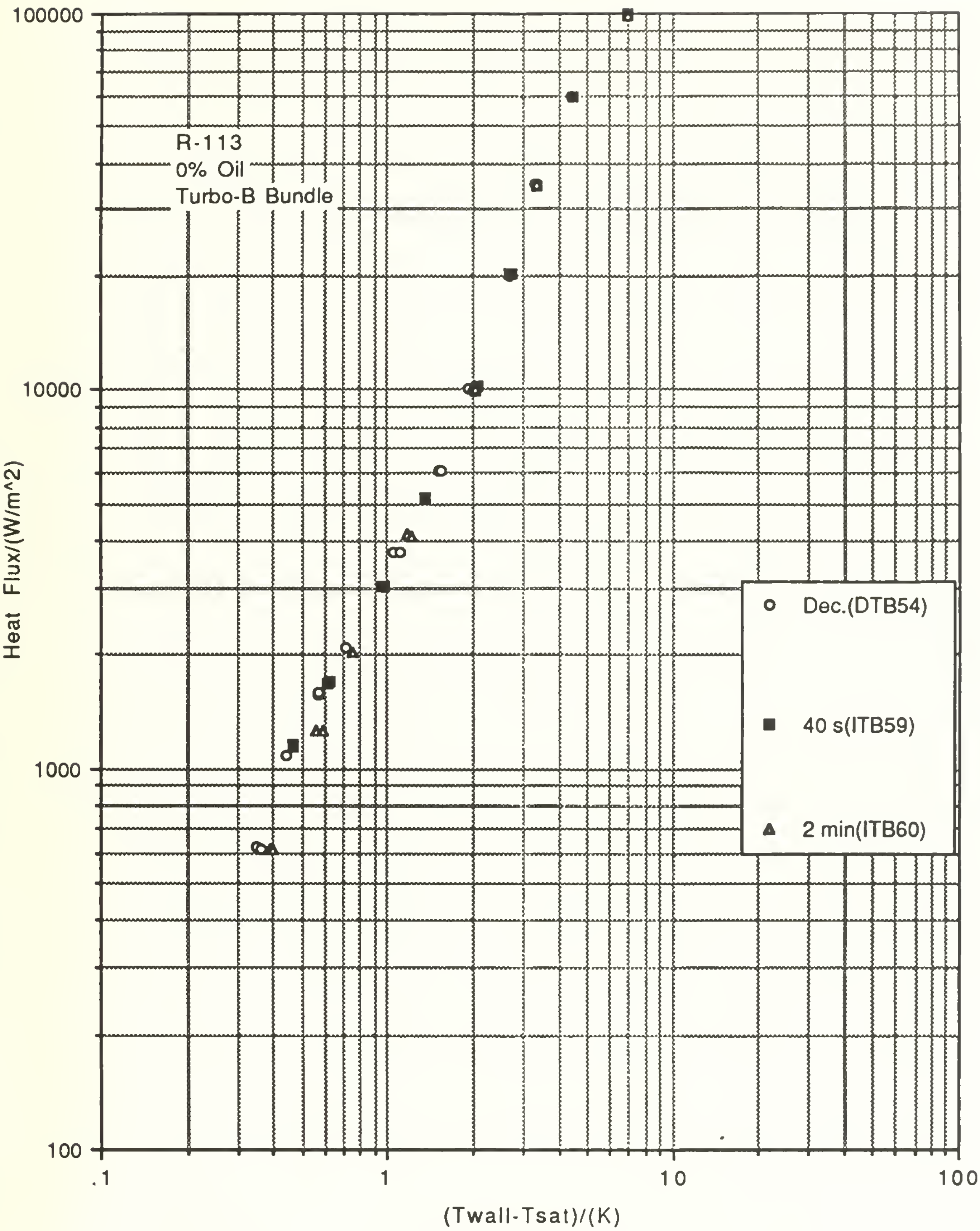

Figure 68. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 0 cm Pool Height

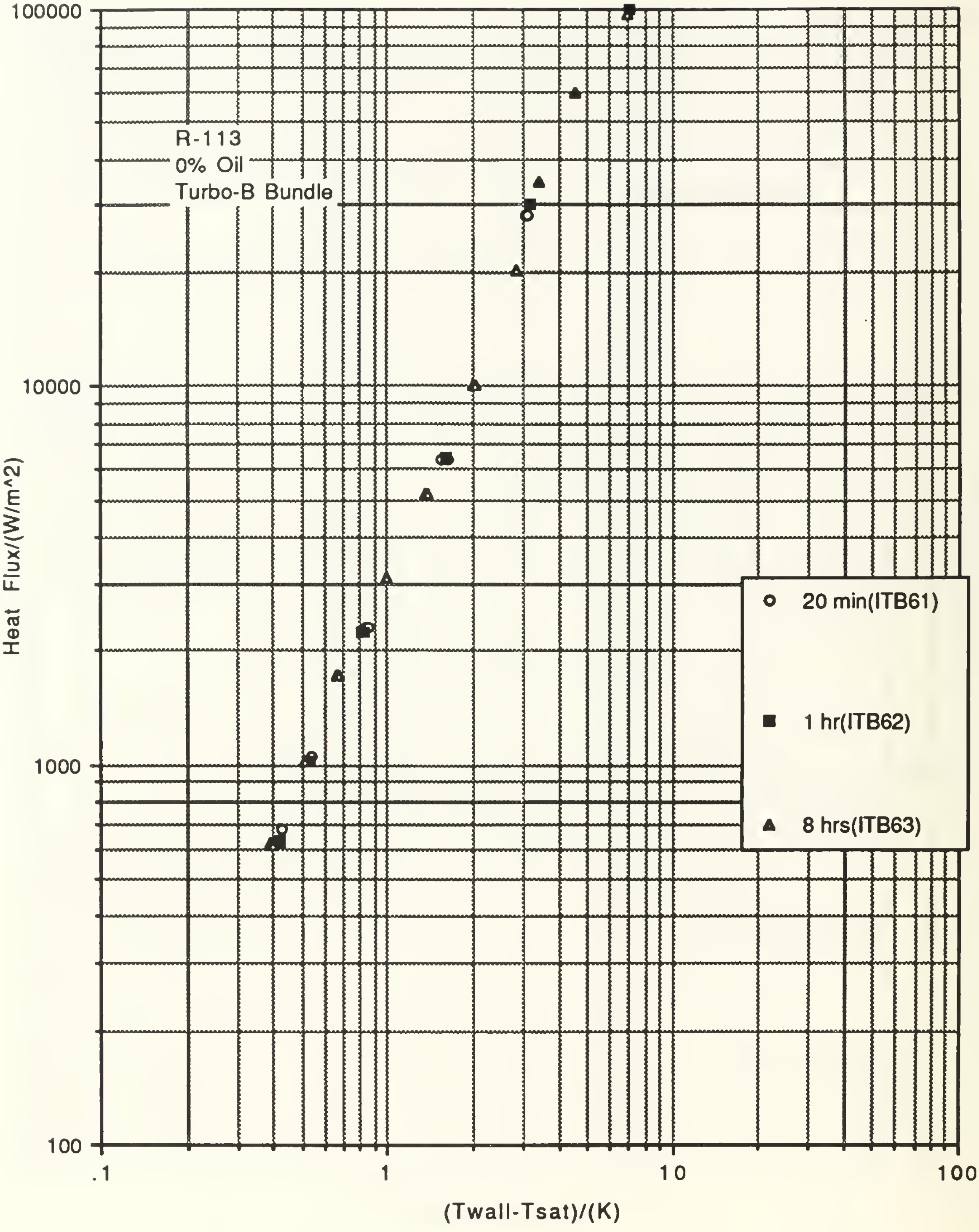

Figure 69. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 0 cm Pool Height

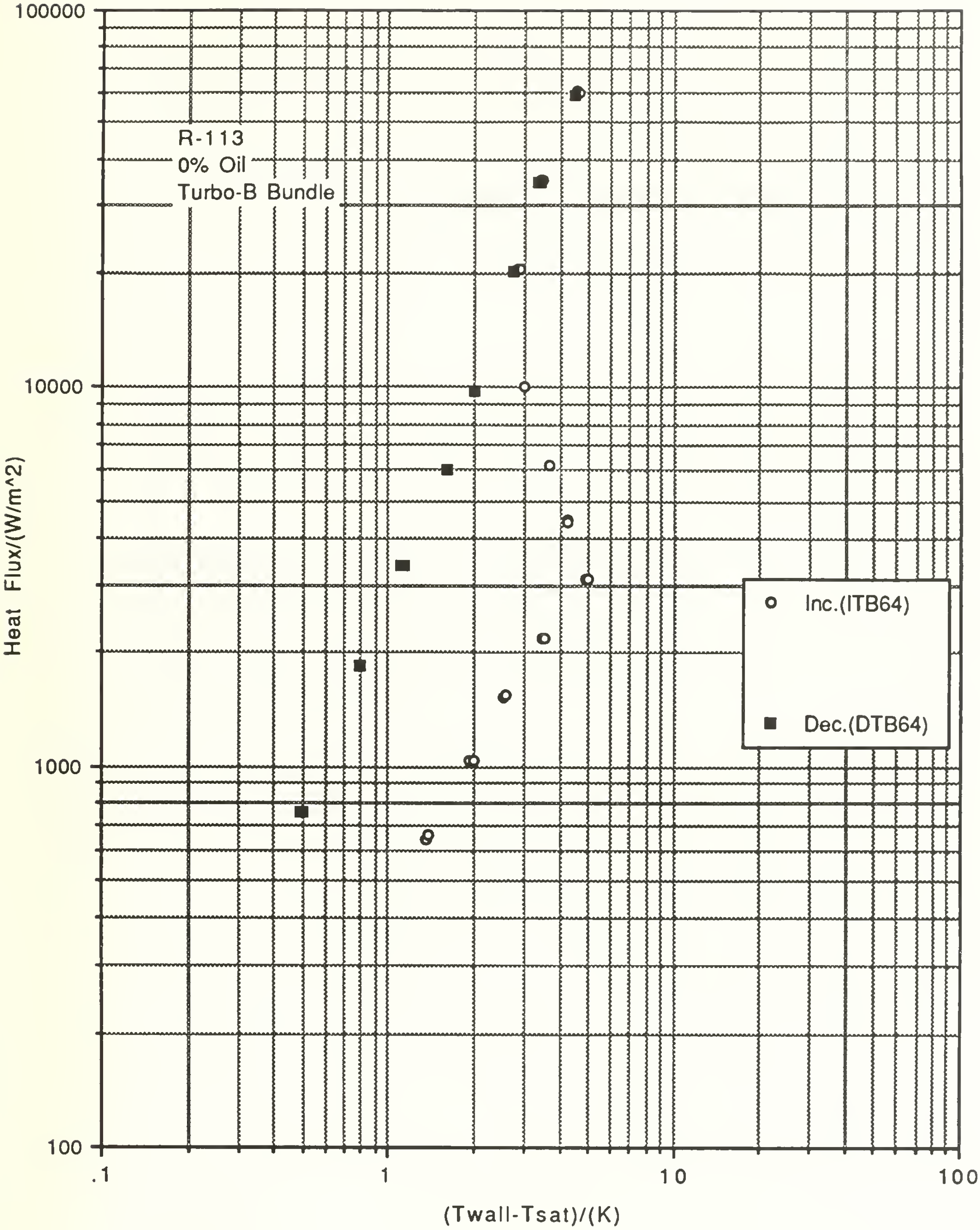

Figure 70. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 0 cm Pool Height

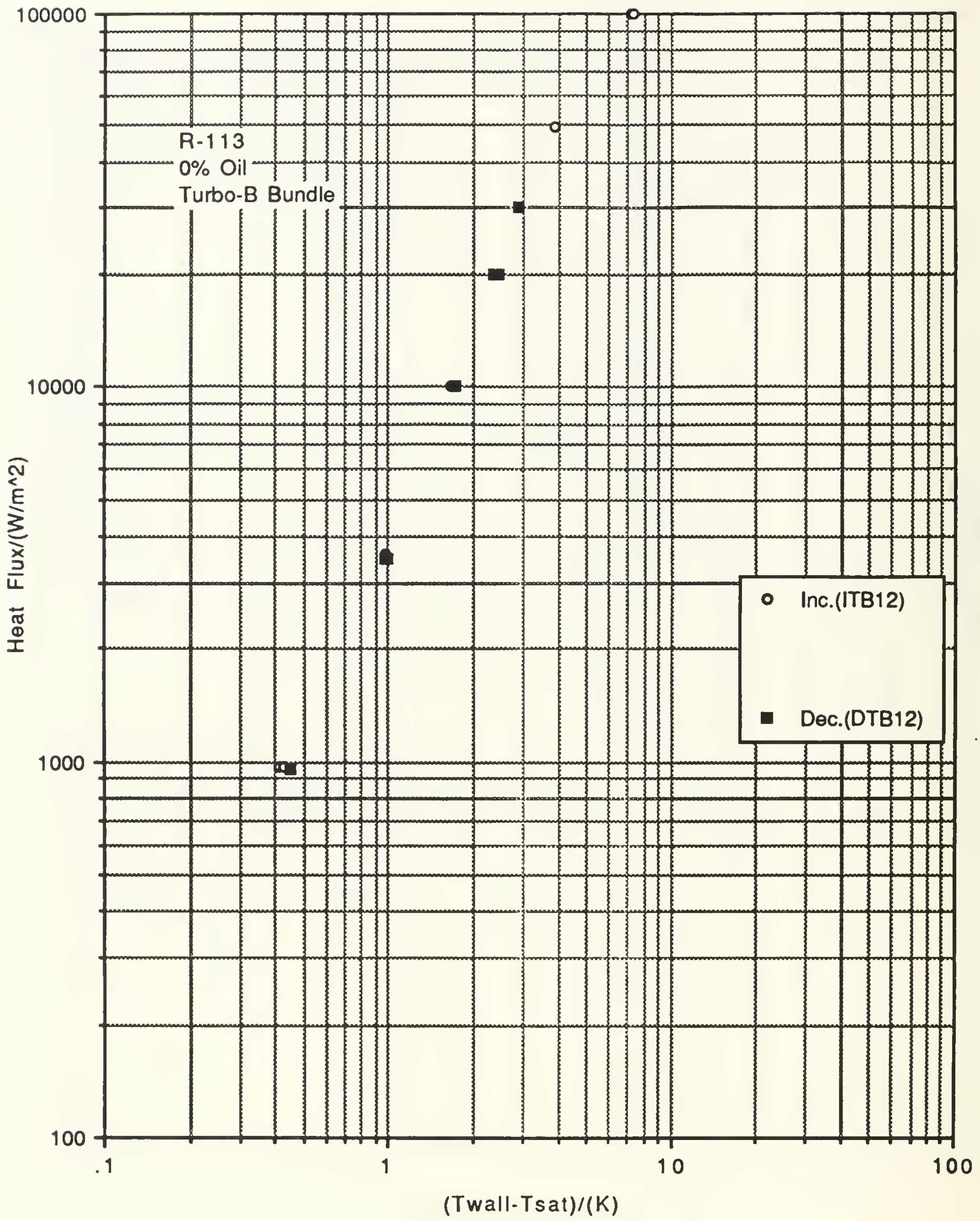

Figure 71. Nucleation Site Deactivation with a 3 kW Auxiliary Heater Setting and a 10 cm Pool Height

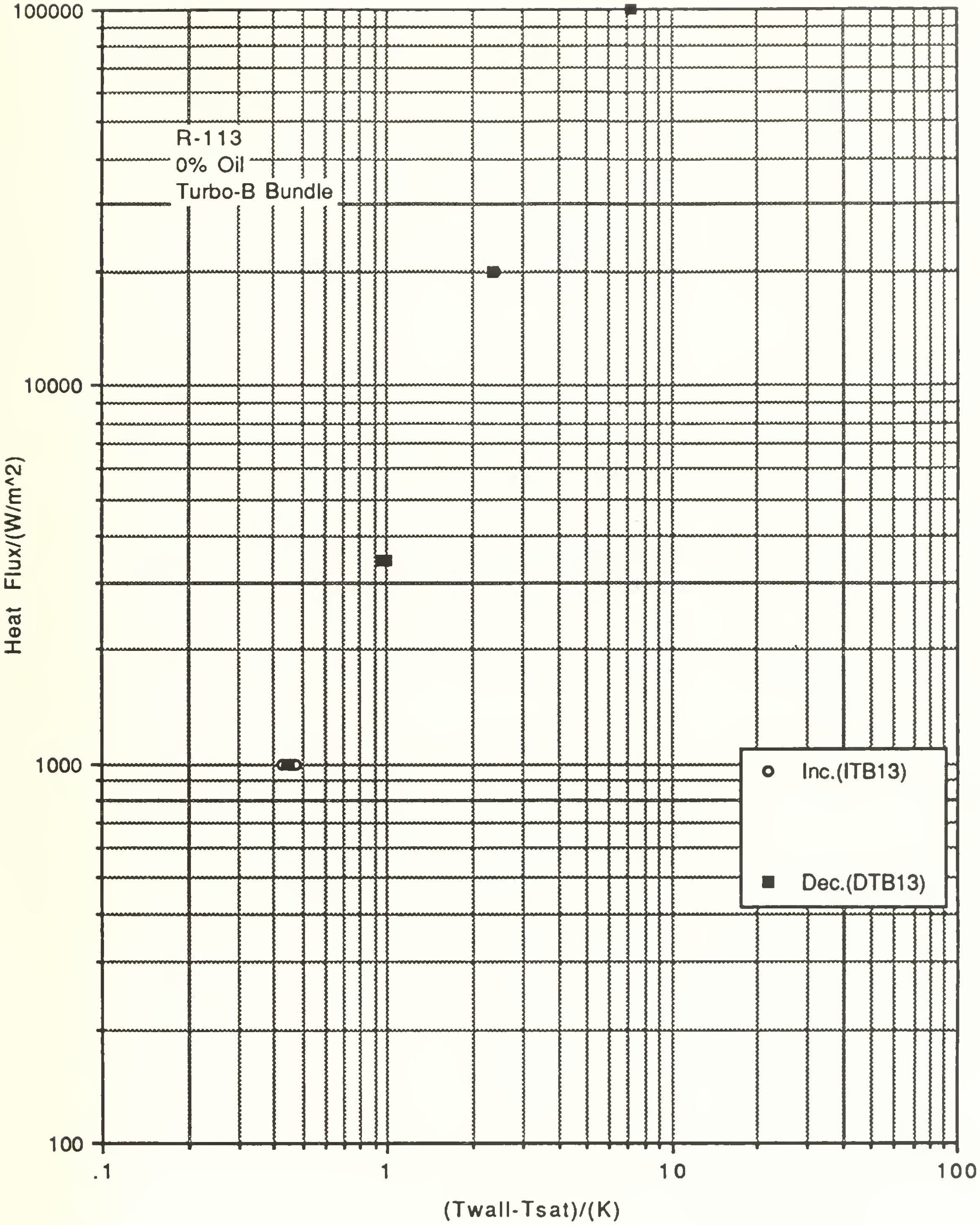

Figure 72. Nucleation Site Deactivation with a 3 kW Auxiliary Heater Setting and a 10 cm Pool Height

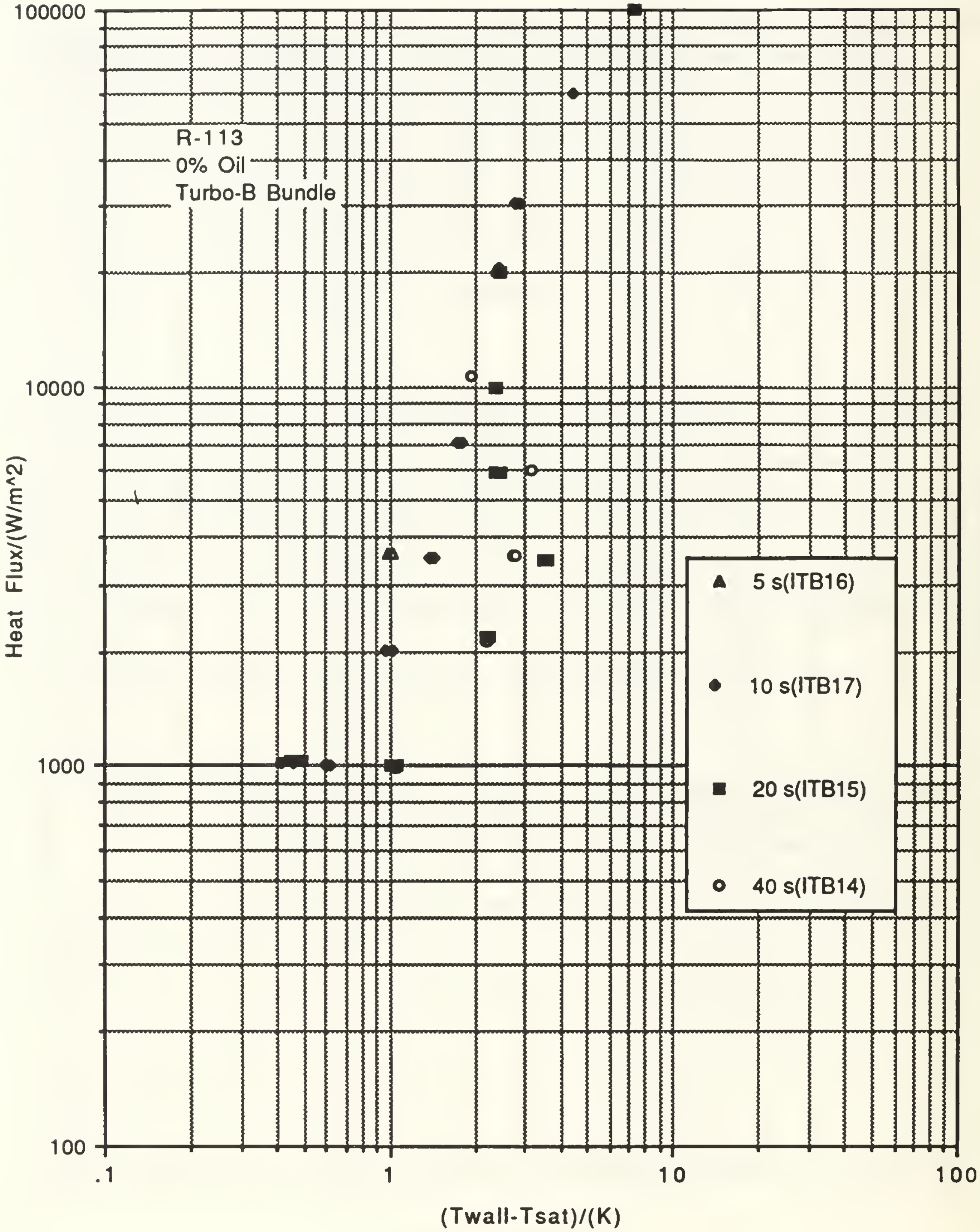

Figure 73. Nucleation Site Deactivation with a 3 kW Auxiliary Heater setting and a 10 cm Pool Height

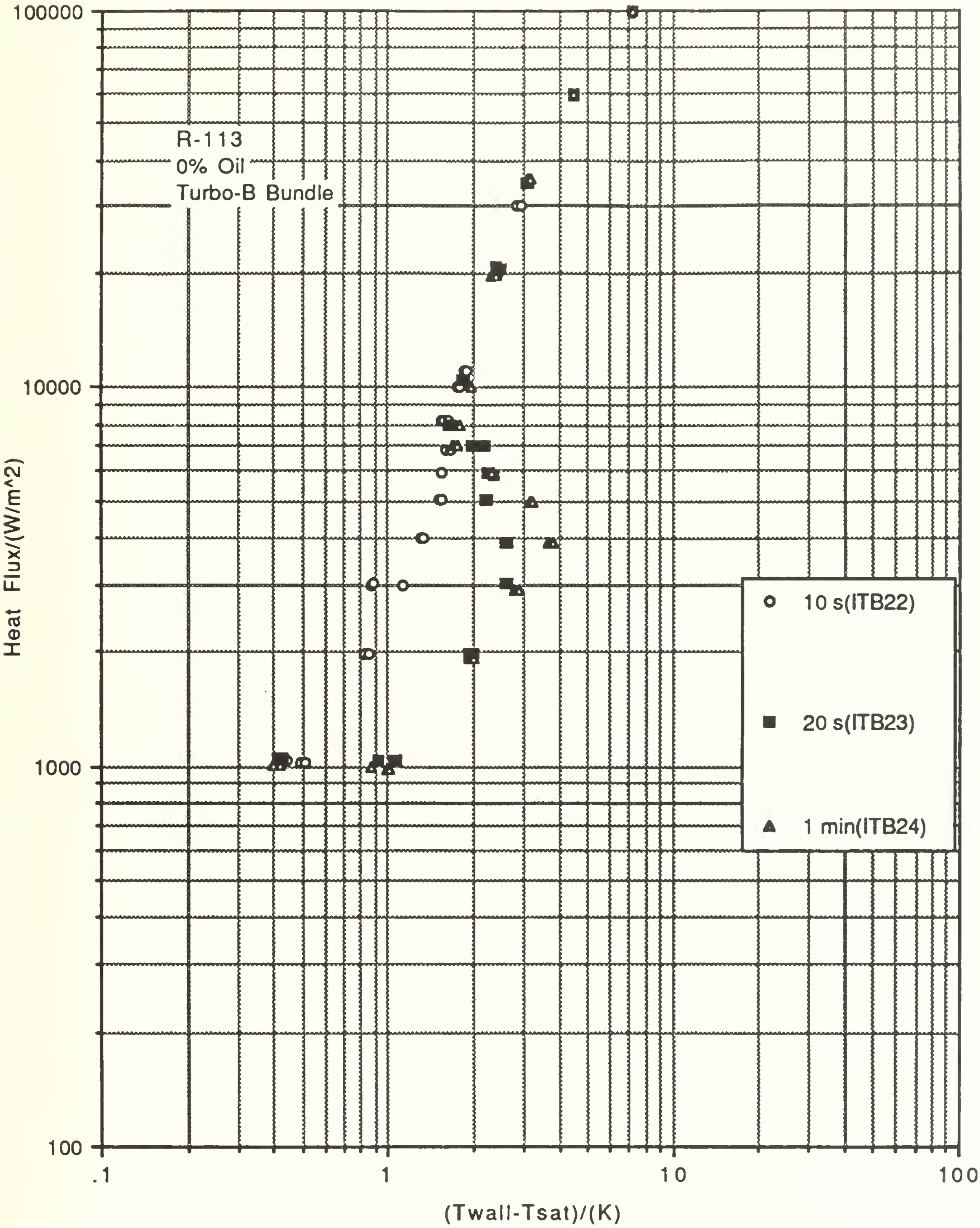

Figure 74. Nucleation Site Deactivation with a 3 kW Auxiliary Heater Setting and a 10 cm Pool Height

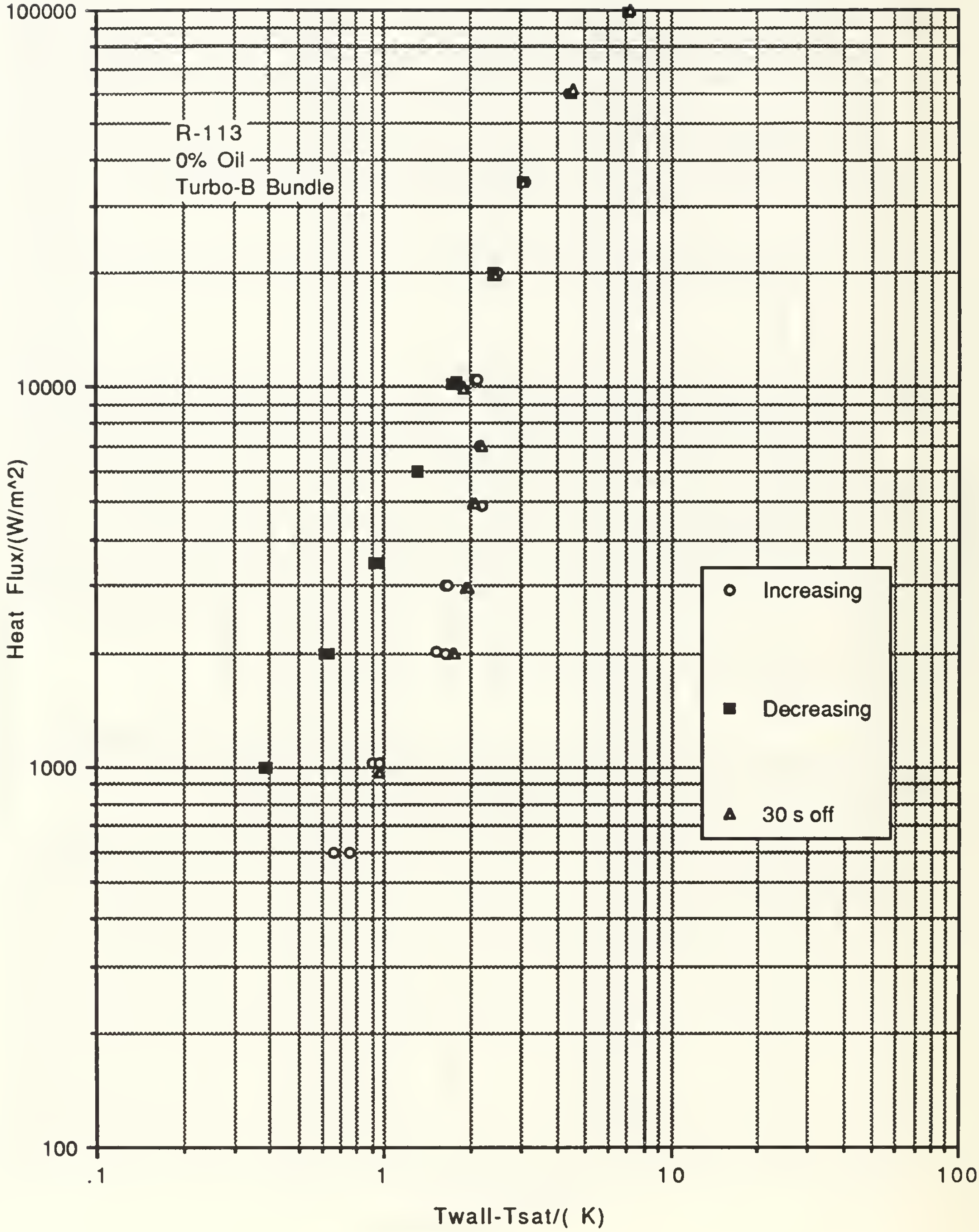

Figure 75. Nucleation Site Deactivation with a 3 kW Auxiliary Heater Setting and a 10 cm Pool Height

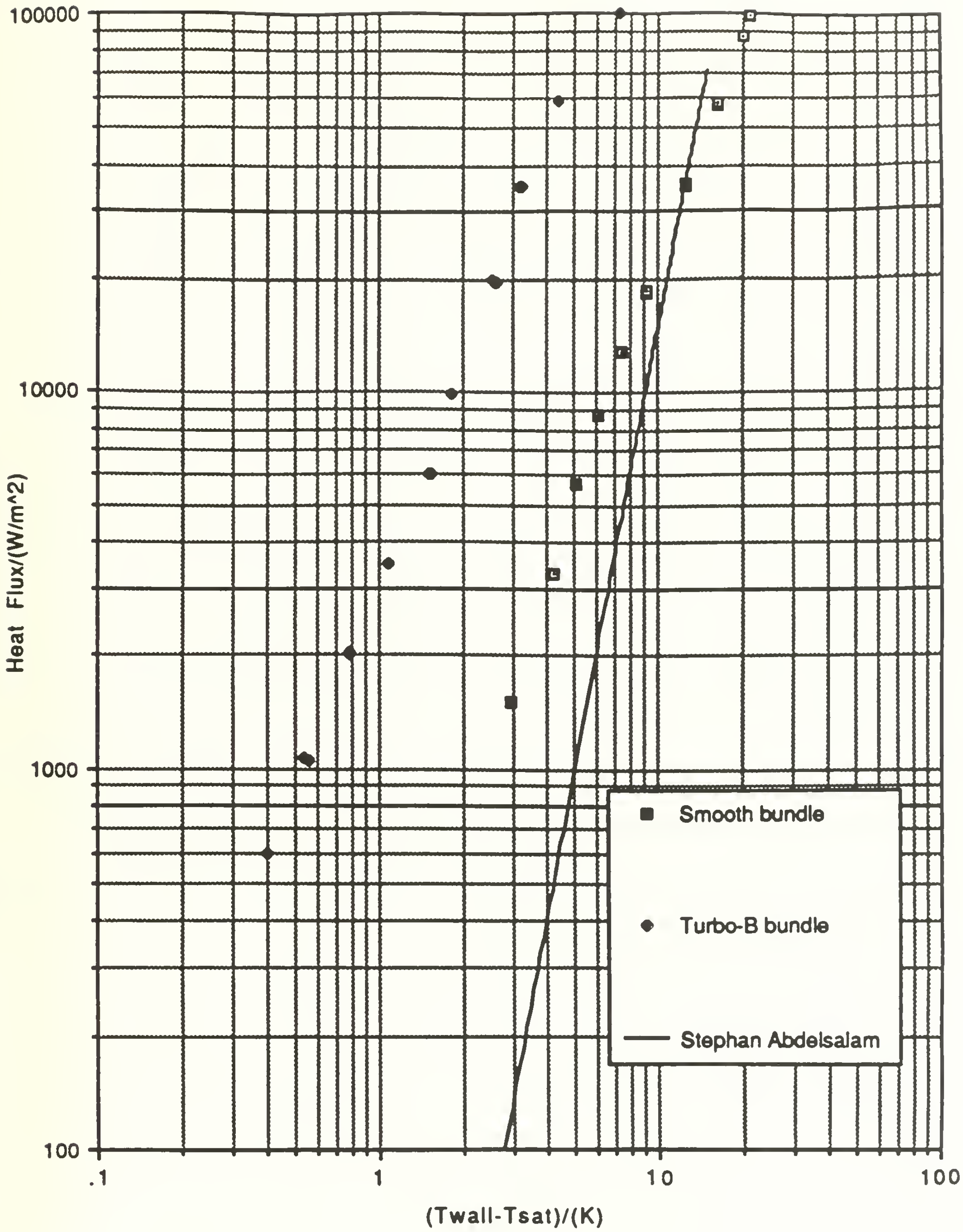

Figure 76. Comparison of Tube 1 During a Decreasing Heat Flux for Smooth vs Turbo-B Bundles in R-113

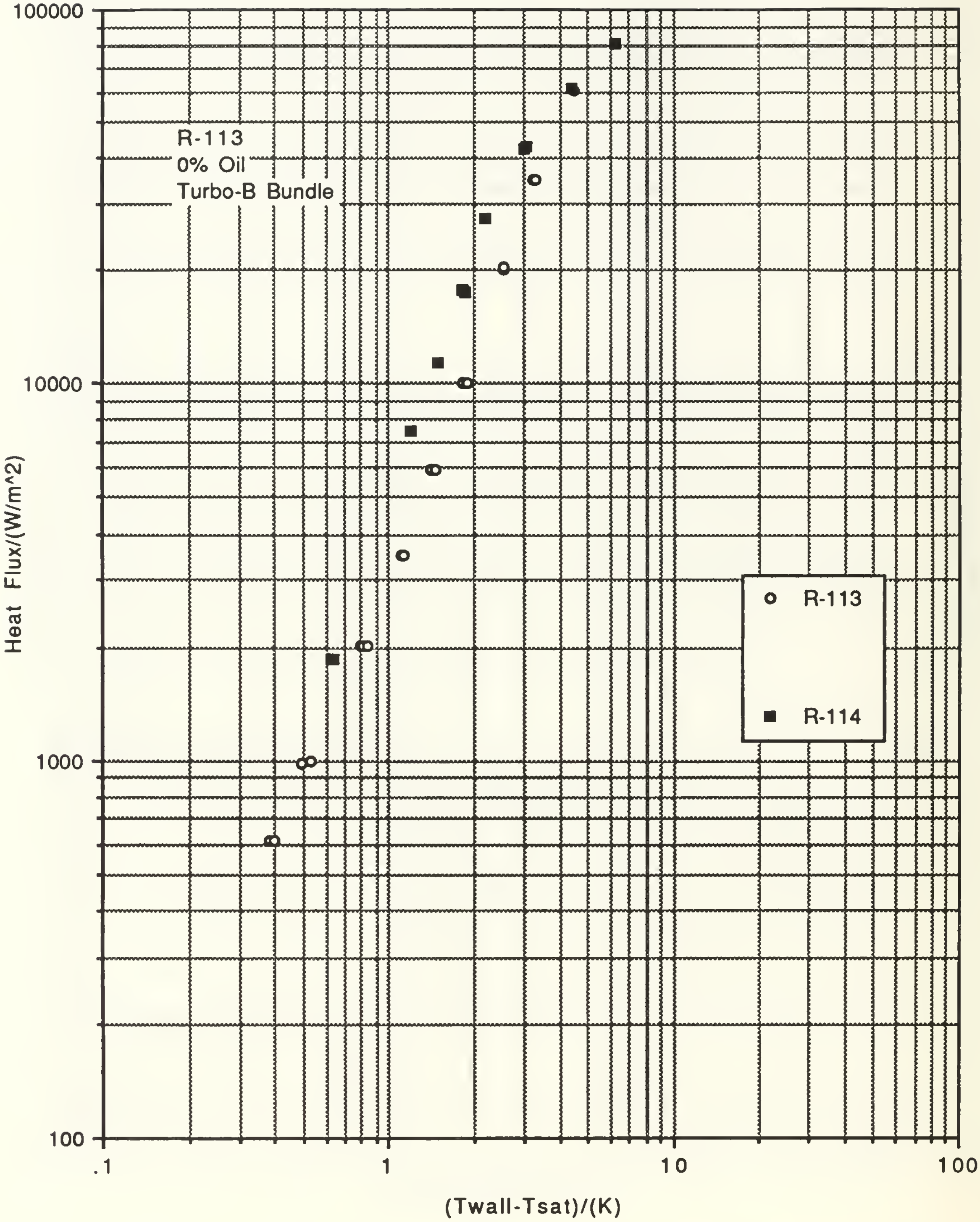

Figure 77. Comparison of Tube 1 During a Decreasing Heat Flux for Turbo-B Tubes in a Bundle with R-113 vs a Bundle for R-114

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. When secured overnight, the bundle exhibited significant temperature overshoot for increasing heat flux (approx. 10°C). The hysteresis loop formed by increasing followed by decreasing heat flux was very repeatable.

2. In the natural convection region, activating lower tubes within the bundle did not affect the upper tubes. However, the heat-transfer coefficient decreased as one moved down the bundle.

3. Activation of the lower tubes caused the upper tubes to nucleate earlier (i.e. at a lower heat flux). As each tube successively nucleated, the heat-transfer performance of the remaining lower tubes improved.

4. In the nucleate boiling region, the performance of the top tube was the best. This performance dropped off steadily as one moved down the bundle.

5. Variation in liquid height above the bundle (from 0 to 20 cm) significantly delayed the point of incipience.

6. For zero pool subcooling, nucleation site deactivation was greatly dependent on both pool height (i.e. pressure head) and tube turn off time. At zero pool height, deactivation was negligible for all time whereas for 10 and 20 cm, there was complete deactivation in 60 and 15 seconds respectively (i.e. decreasing with increasing pool height).

7. At a typical heat flux of 20 kW/m^2, the Turbo-B tube bundle heat-transfer coefficient was approximately four times that of a smooth tube bundle.

8. The uncertainty of the data was greatest at low heat flux and low wall superheat due to the measurement being of the order of accuracy of the thermocouples.

B. RECOMMENDATIONS FOR FUTURE WORK

1. Due to the way a real flooded evaporator operates, it would be preferable to heat the tubes within the bundle with hot water.

2. The pool height tests should be repeated, but by varying the vapor pressure above the liquid, the local pressure at the tube surface should be maintained at a constant value.

3. A pressure test should be conducted and a pressure relief valve fitted to enable the testing of alternative refrigerants such as R-124 which has a higher vapor pressure.

4. Attention needs to be given to the question of refrigerant disposal. There are reclamation projects undertaken by most manufacturers; however, a method still needs to be found to remove the refrigerant from the apparatus into a container for reclamation.

5. Neutrally buoyant particles should be placed in the pool to facilitate study of the circulation patterns within the bundle in more detail.

6. A high speed camera should be used to study the nucleation process and circulation patterns in more detail (the mechanical engineering department is hoping to purchase such a camera in the near future).

7. A sight glass should be fitted to the refrigerant storage tank.

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APPENDIX A: LISTING OF DATA FILES

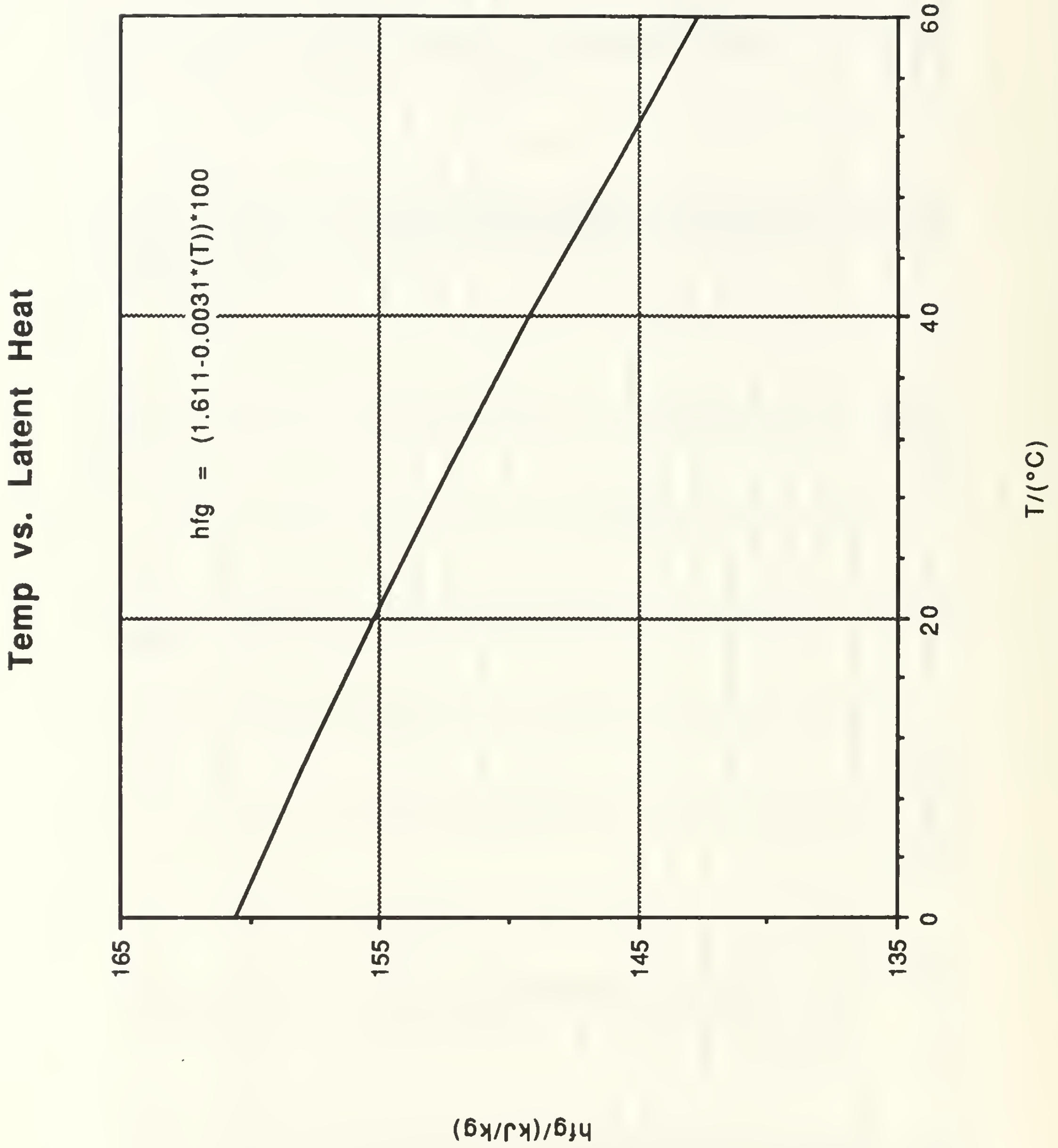
File Name	Data Points	Number of Instrumented Tube Heaters	Pairs of Active Tube Heaters	Number of Simulation Heaters	Auxiliary Heater Setting (nominal)	Pool Height in centimeters (nominal)	Time Tube Heaters were Deactivated
ITB01	17	1	0	0	1kW	10	56 hrs
DTB01	18	1	0	0	1kW	10	
ITB02	51	1	0	0	1kW	10	98 hrs
DTB02	20	1	0	0	1kW	10	
ITB03	32	1	0	0	1kW	10	30 min
DTB03	21	1	0	0	1kW	10	
ITB04	33	1	0	0	1kW	10	48 hrs
DTB04	22	1	0	0	1kW	10	
ITB05	33	2	0	0	1kW	10	68 hrs
DTB05	21	2	0	0	1kW	10	
ITB06	37	3	0	0	1kW	10	14.5 hrs
DTB06	21	3	0	0	1kW	10	
DTB06T	11	3	0	0	1kW	10	
ITB07	24	4	0	0	1kW	10	24 hrs
DTB07	19	4	0	0	1kW	10	
DTB07T	10	4	0	0	1kW	10	
ITB08	4	1	0	0	1kW	10	20 hrs
ITB09	3	1	0	0	1kW	10	20 hrs
DTB10	14	1	0	0	1kW	10	
ITB12	12	1	0	0	3kW	10	Instan. on-off
DTB12	10	1	0	0	3kW	10	
ITB13	9	1	0	0	3kW	10	Instan. on-off
DTB13	8	1	0	0	3kW	10	

File Name	Data Points	Number of Instrumented Tube Heaters	Pairs of Active Tube Heaters	Number of Simulation Heaters	Auxiliary Heater Setting (nominal)	Pool Height in centimeters (nominal)	Time Tube Heaters were Deactivated
ITB14	14	1	0	0	3kW	10	40s
ITB15	16	1	0	0	3kW	10	20s
ITB16	10	1	0	0	3kW	10	5 s
ITB17	18	1	0	0	3kW	10	10 s
ITB18	16	1	0	0	1kW	10	5 s
DTB18	18	1	0	0	1kW	10	
1TB19	8	1	0	0	1kW	10	10 s
ITB20	16	1	0	0	1kW	10	20 s
ITB21	20	1	0	0	1kW	10	1 min
ITB22	35	1	0	0	3kW	10	10 s
ITB23	31	1	0	0	3kW	10	20 s
ITB24	30	1	0	0	3kW	10	1 min
ITB25	22	1	0	0	3kW	10	116 hrs
DTB25	18	1	0	0	3kW	10	
ITB26	20	1	0	0	3kW	10	30 s
ITB27	28	5	0	0	1kW	10	21 hrs
DTB27	18	5	0	0	1kW	10	
ITB28	18	1	0	0	1kW	10	88 hrs
ITB29	26	1	0	0	1kW	10	30 min
DTB30	18	5	0	0	1kW	10	
ITB31	28	1	0	0	1kW	10	16 hrs
DTB31	20	1	0	0	1kW	10	
ITB34	38	2	0	0	1kW	20	16 hrs

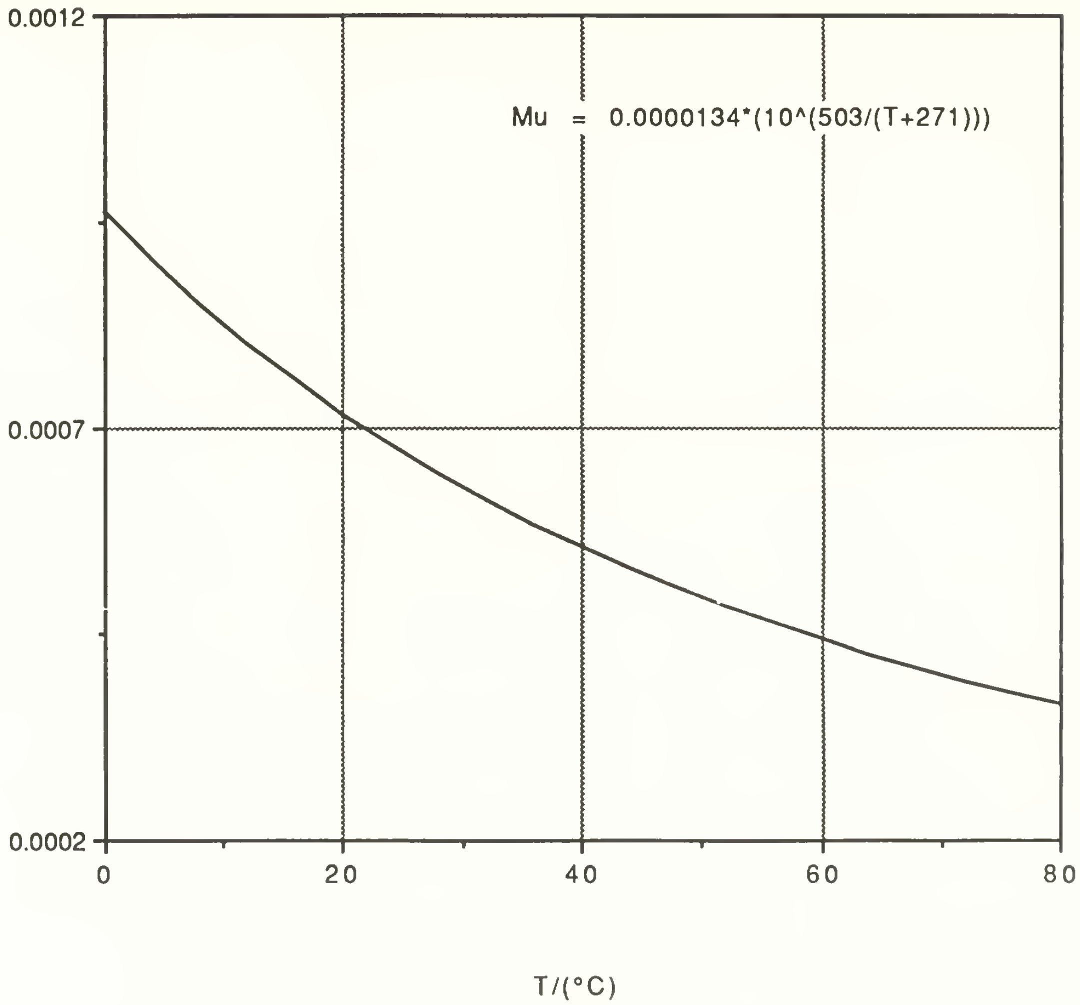
File Name	Data Points	Number of Instrumented Tube Heaters	Pairs of Active Tube Heaters	Number of Simulation Heaters	Auxiliary Heater Setting (nominal)	Pool Height in centimeters (nominal)	Time Tube Heaters were Deactivated
DTB34	20	2	0	0	1kW	20	
ITB35	33	3	0	0	1kW	20	1 hr
DTB35	21	3	0	0	1kW	20	
ITB36	30	4	0	0	1kW	20	2.5 hrs
DTB36	20	4	0	0	1kW	20	
ITB37	28	5	0	0	1kW	20	7 hrs
DTB37	20	5	0	0	1kW	20	
ITB38	32	5	5	0	1kW	20	5 hrs
DTB38	20	5	5	0	1kW	20	
ITB40	31	5	5	5	1kW	20	10 hrs
DTB40	20	5	5	5	1kW	20	
ITB41	27	1	0	0	3kW	20	7.5 hrs
DTB41	20	1	0	0	3kW	20	
DTB32	20	1	0	0	1kW	20	
ITB33	33	1	0	0	1kW	20	20 s
ITB43	15	1	0	0	1kW	20	5 s
ITB44	30	1	0	0	1kW	20	10 s
ITB42	38	1	0	0	1kW	20	14 hrs
ITB45	31	1	0	0	1kW	20	15 s
ITB46	26	1	0	0	1kW	20	15 hrs
ITB47	30	1	0	0	1kW	20	1 hr
ITB48	28	5	5	0	1kW	10	15 hrs
DTB48	20	5	5	0	1kW	10	

File Name	Data Points	Number of Instrumented Tube Heaters	Pairs of Active Tube Heaters	Number of Simulation Heaters	Auxiliary Heater Setting (nominal)	Pool Height in centimeters (nominal)	Time Tube Heaters were Deactivated
ITB49	26	5	5	5	1kW	10	24 hrs
DTB49	20	5	5	5	1kW	10	
ITB51	28	1	0	0	1kW	0	12 hrs
DTB51	20	1	0	0	1kW	0	
ITB52	28	2	0	0	1kW	0	1 hr
DTB52	18	2	0	0	1kW	0	
ITB53	30	3	0	0	1kW	0	15 hrs
DTB53	18	3	0	0	1kW	0	
ITB54	22	1	0	0	1kW	0	10 s
ITB55	29	4	0	0	1kW	0	2 hrs
DTB55	19	4	0	0	1kW	0	
ITB56	27	5	0	0	1kW	0	14.5 hrs
DTB56	18	5	0	0	1kW	0	
ITB57	25	5	5	0	1kW	0	3 hrs
DTB57	18	5	5	0	1kW	0	
ITB58	26	5	5	5	1kW	0	12 hrs
DTB58	18	5	5	5	1kW	0	
ITB59	18	1	0	0	1kW	0	40 s
ITB60	14	1	0	0	1kW	0	2 min
ITB61	12	1	0	0	1kW	0	20 min
ITB62	12	1	0	0	1kW	0	1 hr
ITB63	20	1	0	0	1kW	0	8 hrs
ITB64	24	1	0	0	1kW	0	2.75 hrs
DTB64	18	1	0	0	1kW	0	

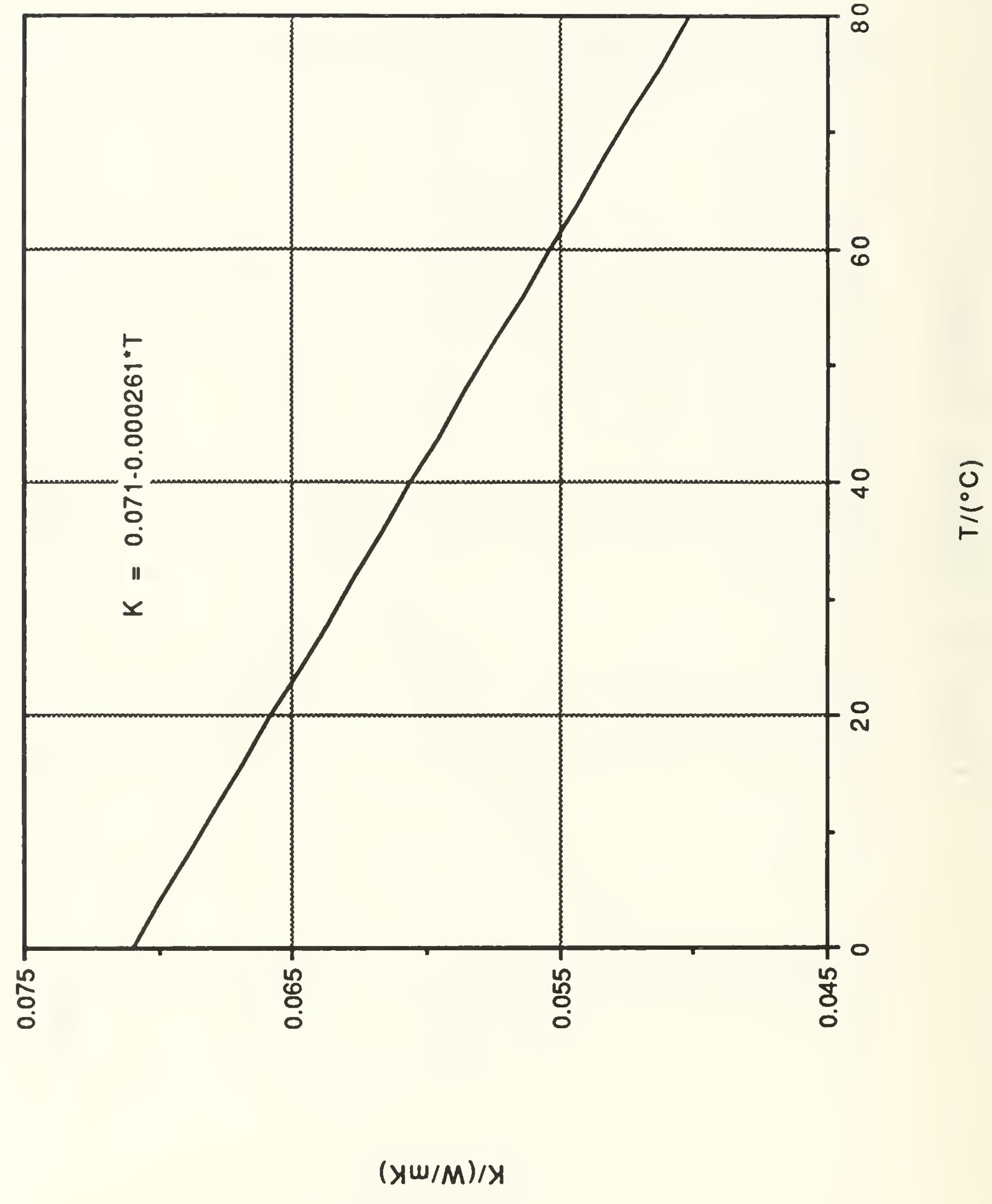
APPENDIX B: PROPERTIES OF R-113

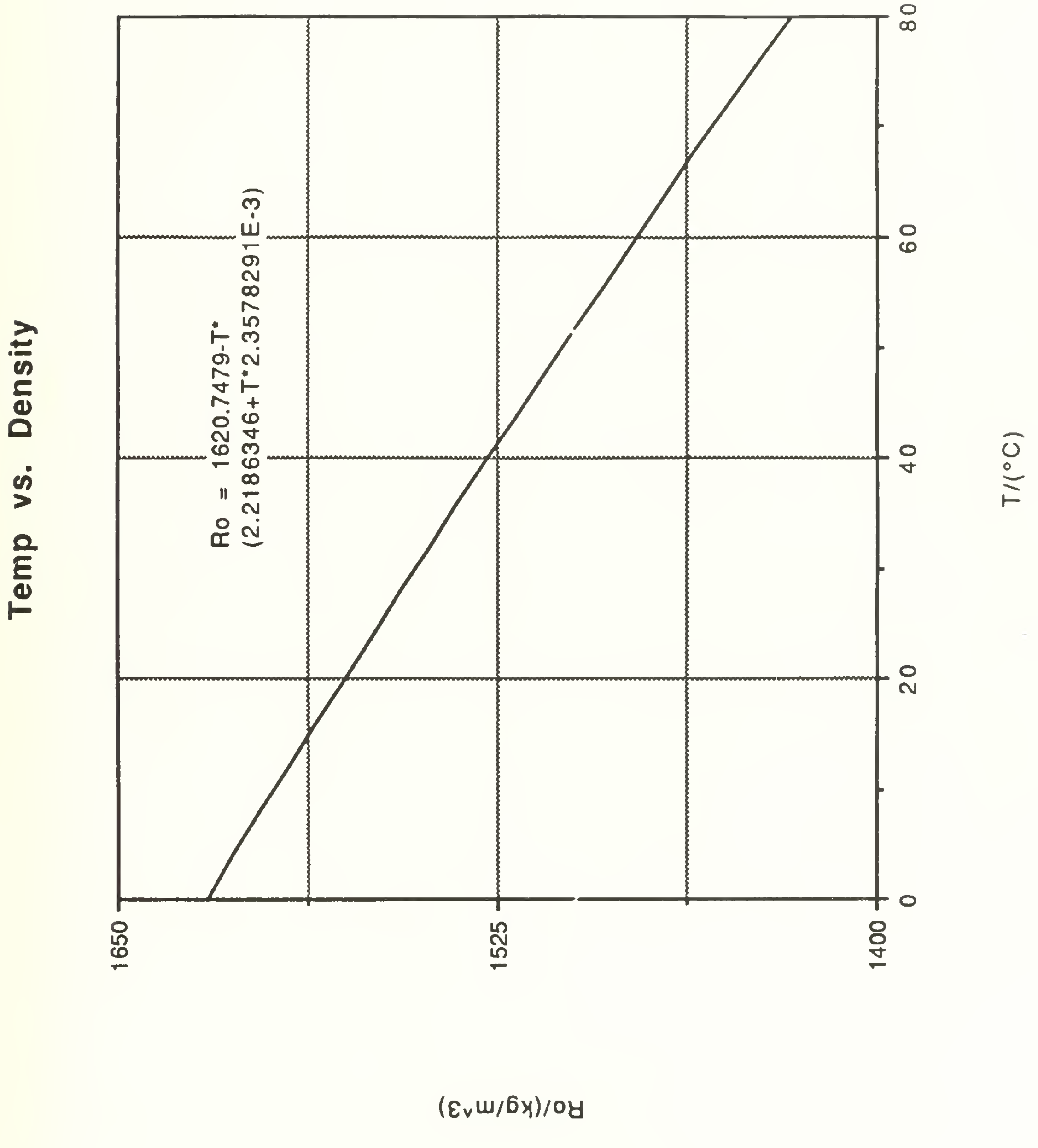


Temp vs. Dynamic Viscosity

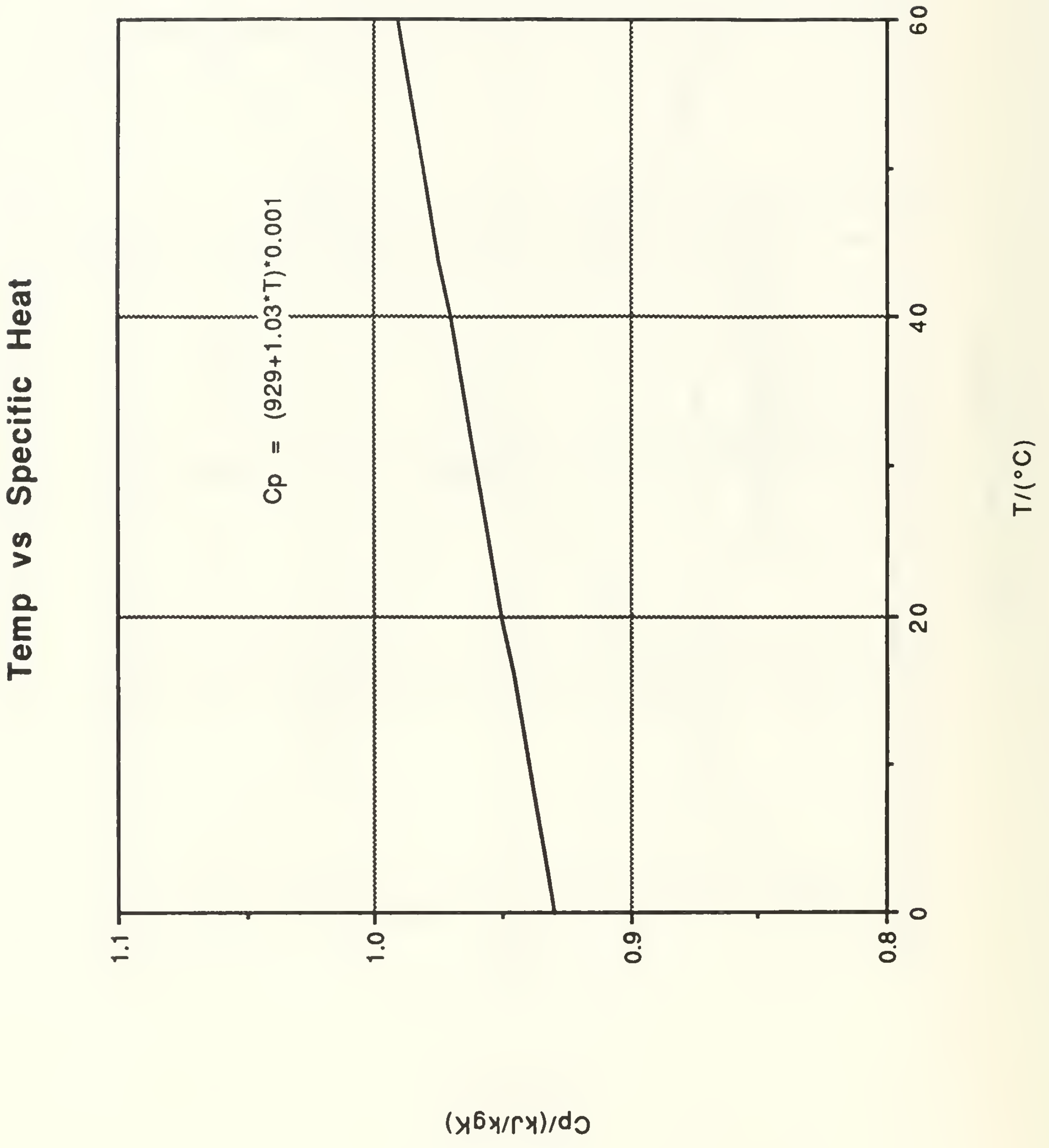


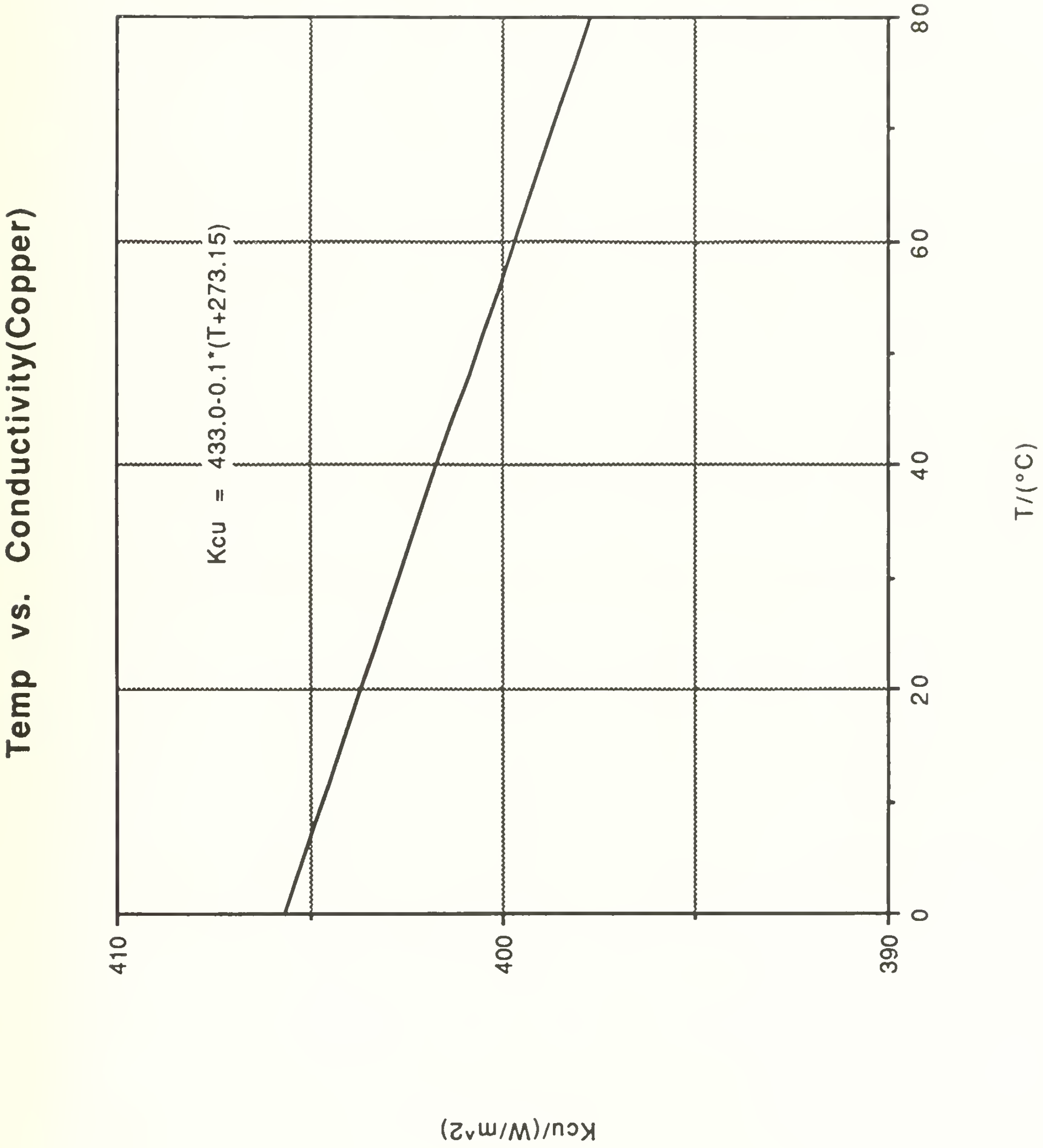
Temp vs. Conductivity(R-113)



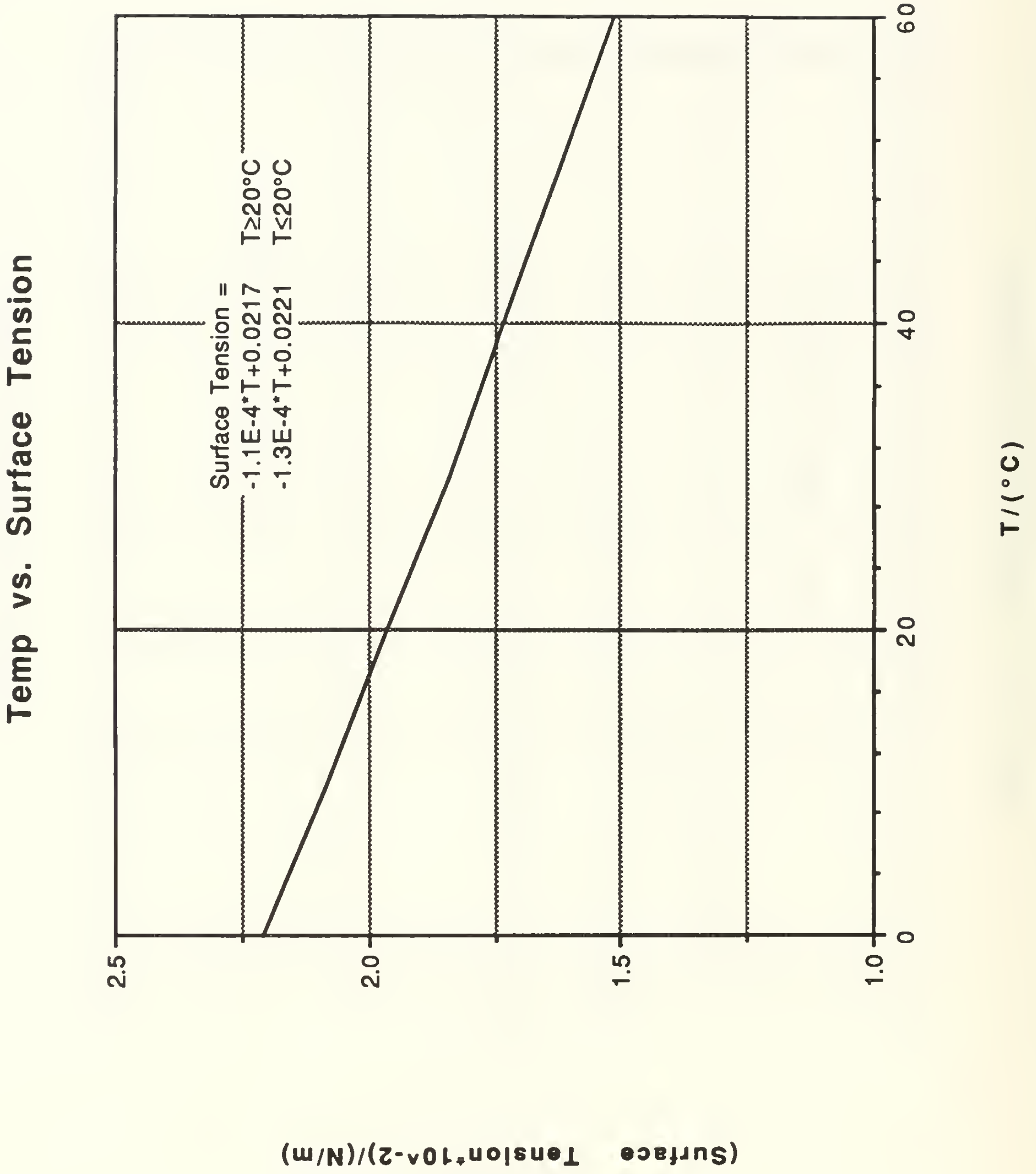


Temp vs. Density
Ro = 1620.7479-T*
(2.2186346+T*2.3578291E-3)
1650
1525
1400
0
20
40
60
80
T/(°C)
Ro/(kg/m^3)


Temp vs Specific Heat
Cp = (929+1.03*T)*0.001
Cp/(kJ/kgK)
1.1
1.0
0.9
0.8
T/(°C)
0
20
40
60

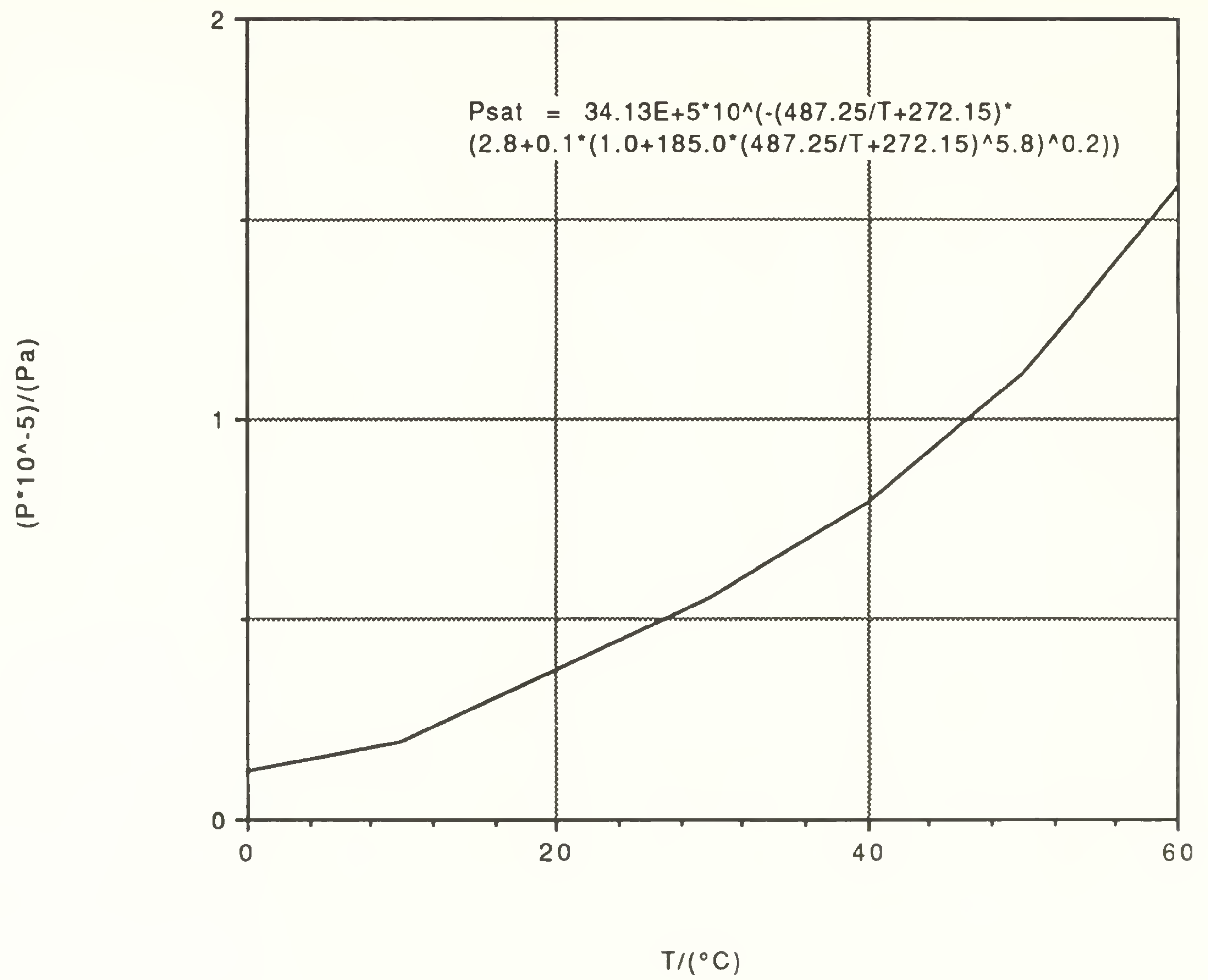


Temp vs. Conductivity(Copper)
Kcu = 433.0-0.1*(T+273.15)
410
400
390
0
20
40
60
80
T/(°C)
Kcu/(W/m^2)



Temp vs. Surface Tension
Surface Tension =
-1.1E-4*T+0.0217 T≥20°C
-1.3E-4*T+0.0221 T≤20°C
2.5
2.0
1.5
1.0
0
20
40
60
T/(°C)
(Surface Tension*10^-2)/(N/m)

Temp vs. Pressure



APPENDIX C: SAMPLE CALCULATIONS

Data set number 1 of run DTB03 (Decreasing heat flux, Turbo-B tube, Surface preparation D) was used for the sample calculations in order to validate the program used for data acquisition DRP4A. The working fluid was R-113.

1. Test tube dimensions

$D_{tc} = 11.60$ mm

$D_o = 14.15$ mm

$D_i = 12.70$ mm

$L = 203.2$ mm

$Lu = 25.4$ mm

2. Measured Parameters

T1 = 54.41 °C

T2 = 55.25 °C

T3 = 55.80 °C

T4 = 55.15 °C

T5 = 55.04°C

T6 = 55.38°C

Tld1 = 47.46°C

Tld2 = 47.48°C

Aas = 3.838V

Vas = 3.958V

3. Calculations

The heater power is first calculated from

$$q = Vas(V) \times Aas(V) \times 60(V/V) \times 1(A/V)$$

Note: The multiplication factors of volt and amp sensors are 60 and 1, respectively.

Therefore:

$$q = 3.958V(3.838V)(60V/V)(1A/V)$$

$$= 911.45W$$

The tube inside wall temperature is obtained from the average of all six thermocouple readings.

$$\overline{T}wi = \frac{1}{6}\sum_{n=1}^{6} Tn$$

$$= 1/6\ (54.41 + 55.25 + 55.80 + 55.15 + 55.04 + 55.38)$$

$$= 55.17°C$$

The tube outside temperature is calculated by knowing the inside wall temperature and using Fouriers Conduction law . Uniform radial conduction is assumed.

$$\overline{T}wo = \overline{T}wi - \frac{q\ [\ln(\frac{D_o}{D_{tc}})]}{2\pi(k_{cu})(L)}$$

where the second term on the right hand side is the Fourier conduction term. If we define this term as

$$\Phi = \frac{q\,[\ln(\frac{D_o}{D_{tc}})]}{2\pi(k_{cu})(L)}$$

and

$$\theta_b = \overline{T}wo - Tsat_c$$

where kcu is the thermal conductivity and is calculated as follow

$$kcu = 434.0 - [0.1(\overline{T}wi\text{-}K)]$$

$$= 434.0 - [0.1(328.32)]$$

$$= 401.17 \text{ W/mK}$$

Now,

$$\overline{T}wo = \overline{T}wi - \frac{911.45[\ln(\frac{14.15}{11.60})]}{2\pi(401.17)(0.2032)}$$

$$= (55.17 - 0.3567)°C$$

$$= 54.82°C$$

The liquid saturation temperature at the top of the tube bundle is

$$Tsat = \frac{Tld1 + Tld2}{2}$$

$$= \frac{47.46+47.48}{2}$$

$$= 47.47°C$$

In order to calculate the local saturation temperature for each tube, correction factors are needed to account for hydrostatic pressure differences between the tube locations and the liquid free surface. This difference is calculated by:

$$\Delta P = \rho\,(g)(ht)$$

where the density is calculated by

$$\rho = 1620.7479 - Tsat(2.2186346 + Tsat(2.3578291E\text{-}3))$$

Therefore, for Tsat = 47.47°C

$$\rho = 1510.1 \text{ kg/m3}$$

So, for the top tube in the bundle which is 0.0124 m below the thermocouples measuring the pool temperature,

$$\Delta P = 1510.1\ (9.81)(0.0124)$$

$$\Delta P = 183.69 \text{ Pa}$$

For a 183.69 Pa pressure difference,the corrected saturation temperature is obtained by adding 0.054°C (obtained from standard tables for R-113 or by equations shown in Appendix F.) to Tsat. The corrected Tsat is:

$$Tsat_c = (Tsat + 0.054)°C$$

$$= (47.47 + 0.054)°C$$

$$Tsat_c = 47.52°C$$

Therefore, the wall superheat can be obtained by the following

$$\theta_b = \overline{T}wo - Tsat_c$$
$$= (54.82 - 47.52)°C$$
$$= 7.30°C$$

Now that the wall superheat is known, we need to calculate the heat flux and the heat transfer coefficient. To do this, we know that the tube is 12 inches long and is heated in a eight inch center portion of the tube. The unheated lengths of the tube are a one inch and a three inch section on opposite ends of the tube. These unheated lengths have a fin effect during the heat transfer process to the evaporating refrigerant. In order to account for this, the following procedure was adopted for both the one and three inch sections. Calculations are shown below for the one inch section .

Heat transfer from the unheated end is calculated as heat from the base of a fin:

$$q_f = (h_b \times p \times k_{cu} \times A_c)^{0.5} \times \theta_b \times \tanh(n \times L_c)$$

where

$$p = \pi \times D_o$$
$$= \pi \times 14.15E\text{-}3 \text{ m}$$
$$= 44.45E\text{-}3 \text{ m}$$

now

$$A_c = \frac{\pi}{4}(D_o^2 - D_i^2)$$
$$A_c = \frac{\pi}{4}(0.01415^2 - 0.01270^2)$$
$$A_c = 3.0578E\text{-}5 \text{ m}^2$$

The corrected length of unenhanced surface at the end was calculated as follows

$$L_c = L_u + \frac{t}{2}$$

$$L_c = 0.0254 + \frac{(0.01415\text{-}0.0127)}{2}$$

$$L_c = 0.0258 \text{ m}$$

h_b is the natural convection heat transfer coefficient of the fin like ends and was calculated by using the Churchill-Chu [Ref. 24] correlation for natural convection from a smooth horizontal cylinder, as modified by Pulido [Ref. 27].

$$h_b = \frac{k}{D_o}\left[0.6 + 0.387 \times \frac{\left[\frac{g \times \beta \times D_o^3 \times \theta_b \times \tanh(n \times L_c)}{\nu \times \alpha \times L_c \times n}\right]^{\frac{1}{6}}}{\left[1 + \left[\frac{0.559}{Pr}\right]^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right]^2$$

where

$$n = \left[\frac{h_b \times p}{k_{cu} \times A_c}\right]^{0.5}$$

Therefore an iterative technique was necessary to calculate h_b. The iterative technique used was to assume h_b was 190 $\frac{W}{m^2K}$ and to continue the iteration until successive values are within 0.001 of each other. The fluid physical properties are calculated at the vapor mean film temperature, given by the following equation.

$$T_{film} = \frac{Tsat_c + \overline{T}wo}{2}$$

$$T_{film} = \frac{47.52 + 54.82}{2}$$

$$T_{film} = 51.17°C = 324.32°K$$

For R-113, the physical properties are given in the program by

Dynamic viscosity, T_{film} in °K

$$\mu = 1.34E\text{-}5 \times 10^{\left[\frac{503}{T_{filmK} - 2.15}\right]}$$

$$\mu = 4.88E\text{-}4 \text{ kg/m·s}$$

Specific heat, T_{film} in °C

$$Cp = 929.0 + (1.03 \text{ x } T_{film})$$

$$Cp = 981.71 \text{ J/kg·K}$$

Density, T_{film} in °C

$$\rho = 1620.7479 - T_{film}[2.2186346 + T_{film}(0.0023578291)]$$

$$\rho = 1501.1 \text{ kg/m}^3$$

Thermal conductivity of R-113, T_{film} in °C

$$k = 0.071 - (0.000261 \text{ x } T_{film})$$

$$k = 5.765E\text{-}2 \text{ W/mK}$$

Prandtl number

$$Pr = C_p \times \frac{\mu}{k}$$

$$Pr = 981.71 \times \frac{4.88E\text{-}4}{5.7645E\text{-}2}$$

$$Pr = 8.31$$

Thermal expansion

$$\beta = -(1/\rho)(\Delta\rho/\Delta T)$$

$$\rho_{51.07} = 1501.29 \text{ kg/m}^3 \qquad \rho_{51.27} = 1500.8 \text{ kg/m}^3$$

$$\beta = -(1/1501.1)(0.49/0.2)$$

$$\beta = 1.63E\text{-}3 \ (1/K)$$

Kinematic viscosity

$$\nu = \frac{\mu}{\rho}$$

$$\nu = \frac{4.88E\text{-}4}{1501.1}$$

$$\nu = 3.25E\text{-}7 \text{ m}^2/\text{s}$$

Thermal diffusivity

$$\alpha = \frac{k}{\rho \times C_p}$$

$$\alpha = \frac{5.7645E\text{-}2}{1501.1 \times 981.71}$$

$$\alpha = 3.912E\text{-}8 \text{ m}^2/\text{s}$$

Knowing the above properties, the heat transfer coefficient, h_b, can be obtained by iteration.

$$h_b = 185.42 \text{ W/m}^2\cdot\text{K}$$

knowing this we calculate n

$$n = \left[\frac{h_b \times p}{k_{cu} \times A_c}\right]^{0.5}$$

$$n = \left[\frac{185.42 \times 44.45E\text{-}3}{401.17 \times 3.0578E\text{-}5}\right]^{0.5}$$

$$n = 25.92$$

then we can obtain q_f

$$q_f = (h_b \times p \times k_{cu} \times A_c)^{0.5} \times \theta_b \times \tanh(n \times L_c)$$

$$q_f = (185.42 \times 44.45E\text{-}3 \times 401.17 \times 3.0578E\text{-}5)^{0.5} \times 7.3 \times \tanh(25.92 \times 0.0258)$$

$$q_f = 1.36 \text{ W}$$

The corresponding results for the three inch section are

$$h_b = 158.27 \text{ W/m}^2\cdot\text{K}$$

$$q_f = 2.04 \text{ W}$$

Therefore the heat transfer through the heated length of the tube is

$$q_s = q - qf(1 \text{ inch section}) - qf(3 \text{ inch section})$$

$$q_s = (911.45 - 1.36 - 2.04) \text{ W}$$

$$q_s = 908 \text{ W}$$

and the heat flux and the heat transfer coefficient are as follows

$$q'' = q_s/A_s$$

$$= q_s/(\pi \times D_o \times L)$$

$$= 908/(\pi \times 0.01415 \times 0.2032)$$

$$= 908/9.033E\text{-}3$$

$$= 1.005E{+}5 \text{ W/m}^2$$

and finally the heat transfer coefficient.

$$h = \frac{q_s}{A_s \times (\overline{T}wo\text{-}Tsat)}$$

$$= 908 / (9.033E\text{-}3 \times 7.3)$$

$$h = 1.376E{+}4 \ W/m^2 \cdot K$$

APPENDIX D: UNCERTAINTY ANALYSIS

The same data run (DTB03) was chosen for the uncertainty analysis. Therefore, the measured and calculated parameters found in the sample calculation were used in this section. The uncertainty analysis performed was for a high heat flux but the same procedure could be performed at any heat flux to determine the uncertainty bands. All uncertainties are presented as a percentage of the calculated parameter. The uncertainty associated with the experimental parameters is calculated from the equation suggested by Kline and McClintock [Ref 28]. For example, if

$$R = R\,(x_1, x_2, \ldots, x_n)$$

then

$$\delta R = \left[\left(\frac{\partial R}{\partial x_1}\delta_{x_1}\right)^2 + \left(\frac{\partial R}{\partial x_2}\delta_{x_2}\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}\delta_{x_n}\right)^2 \right]^{0.5}$$

where:

δR = uncertainty of the desired dependant variables

x_n = measured variables

δx_n = uncertainty in measured variables

The boiling heat transfer coefficient is given by

$$h = \frac{q_s}{A_s \times (\overline{T}wo - Tsat)}$$

where

$$\overline{T}wo = \overline{T}wi - \frac{q\,[\ln(\frac{Do}{Dtc})]}{2\pi(kcu)(L)}$$

In the above equation, the second term on the right hand side is usually called the Fourier heat transfer conduction term. If we define this as Φ, then

$$\Phi = \frac{q\,[\ln(\frac{Do}{Dtc})]}{2\pi(kcu)(L)}$$

and

$$\theta_b = \overline{T}wo - Tsat_c$$

With this notation, the uncertainty in the heat transfer coefficient is obtained using the following equation.

$$\frac{\delta h}{h} = \left[\left[\frac{\delta q}{q}\right]^2 + \left[\frac{\delta A_s}{A_s}\right]^2 + \left[\frac{\delta \overline{T}wi}{\theta_b}\right]^2 + \left[\frac{\delta \Phi}{\theta_b}\right]^2 + \left[\frac{\delta Tsat}{\theta_b}\right]^2\right]^{\frac{1}{2}}$$

where

$$q = V \times I$$

$$q = V(V) \times I(V) \times 60(V/V) \times 1(A/V)$$

and the uncertainty is

$$\frac{\delta q}{q} = \left[\left[\frac{\delta V}{V}\right]^2 + \left[\frac{\delta I}{I}\right]^2\right]^{\frac{1}{2}}$$

The accuracy in the voltage and current sensors are as follows

$\delta Vas = \pm 0.05$ V $\qquad\qquad$ $\delta Aas = \pm 0.025$ A

From the sample calculation section

$Vas = 3.958V$ $Aas = 3.838V$

Therefore,

$$\delta q/q = ((\delta Vas/Vas)^2 + (\delta Aas/Aas)^2)^{0.5}$$

$$\delta q/q = ((0.05/3.958)^2 + (0.025/3.838)^2)^{0.5}$$

$$\delta q/q = 1.42 \text{ percent}$$

Calculation of the surface area and the uncertainty of it are done as follows

$$As = \pi \times D_o \times L$$

$$\frac{\delta As}{As} = \left[\left[\frac{\delta Do}{Do}\right]^2 + \left[\frac{\delta L}{L}\right]^2\right]^{\frac{1}{2}}$$

Knowing the dimensions of the tube from the manufacturer and estimated inaccuracies from work shop tools and human error, the uncertainty was calculated.

Dimensions

$D_o = 14.15$ mm $L = 203.2$ mm

Inaccuracies in measurements

$\delta D_o = 0.1$ mm $\delta L = 0.2$ mm

Uncertainty analysis performed

$$\delta A_s/A_s = ((\delta D_o/D_o)^2 + (\delta L/L)^2)^{0.5}$$

$$\delta A_s/A_s = ((0.1/14.15)^2 + (0.2/203.2)^2)^{0.5}$$

$$\delta A_s/A_s = 0.7135 \text{ percent}$$

The uncertainty calculation for the Fourier conduction term is given below

$$\frac{\delta\Phi}{\Phi} = \left[\left[\frac{\delta q}{q}\right]^2 + \left[\frac{\delta\, kcu}{kcu}\right]^2 + \left[\frac{\delta L}{L}\right]^2\right]^{\frac{1}{2}}$$

kcu was calculated using

$$k_{cu} = 434.0 - [0.1(\overline{T}wi\text{-}K)]$$

$$= 434.0 - [0.1(328.32)]$$

$$= 401.17 \text{ W/mK}$$

and its uncertainty

$$\delta kcu = \left[(0.1 \times \delta\overline{T}wi\text{-}K)^2\right]^{\frac{1}{2}}$$

$\delta\overline{T}wi$ and $\delta Tsat$ are obtained using uncertainties in the thermocouple readings. Average wall inside temperature $\overline{T}wi$ was obtained taking the average of six thermocouple readings inside the tube. The uncertainty associated with this variable is

$$\delta\overline{T}wi = \left[6 \times \left[\frac{\delta T_c}{6}\right]^2\right]^{\frac{1}{2}}$$

where δT_c was obtained as ± 0.5°C from "Omega 1987 Complete Temperature Measurements Handbook pp. T-37. Using engineering judgement this seems high will use 0.1°C.

$$\delta\overline{T}wi = \left[6 \times \left[\frac{0.1}{6}\right]^2\right]^{\frac{1}{2}}$$

$$\delta\overline{T}wi = 0.04\ ^{\circ}C$$

Saturation temperature was obtained by taking the average of two thermocouple readings and the uncertainty in this temperature was calculated from the following equation.

$$\delta Tsat = \left[2 \times \left[\frac{\delta T_c}{2}\right]^2\right]^{\frac{1}{2}}$$

$$\delta Tsat = \left[2 \times \left[\frac{0.1}{2}\right]^2\right]^{\frac{1}{2}}$$

$$\delta Tsat = 0.07^{\circ}C$$

Knowing the uncertainty in the temperatures, we can now calculate the uncertainties in the following.

$$\delta kcu = \left[(0.1 \times \delta\overline{T}wi\text{-}K)^2\right]^{\frac{1}{2}}$$

$$\delta kcu = \left[(0.1 \times 273.19)^2\right]^{\frac{1}{2}}$$

$$\delta kcu = 27.32\ W/mK$$

Now we can calculate the uncertainty in the Fourier conduction term

$$\frac{\delta\Phi}{\Phi} = \left[\left[\frac{\delta q}{q}\right]^2 + \left[\frac{\delta\, kcu}{kcu}\right]^2 + \left[\frac{\delta L}{L}\right]^2\right]^{\frac{1}{2}}$$

$$\frac{\delta\Phi}{\Phi} = \left[[0.0142]^2 + \left[\frac{27.32}{401.17}\right]^2 + \left[\frac{0.2}{203.2}\right]^2\right]^{\frac{1}{2}}$$

$$\frac{\delta\Phi}{\Phi} = 6.96 \text{ percent}$$

from the sample calculations we know that $\Phi = 0.3567$ °C or

$$\delta\Phi = 0.3567 \times 6.96 \text{ percent} = 0.025 \text{ °C}$$

therefore:

$$\frac{\delta h}{h} = \left[\left[\frac{\delta q}{q}\right]^2 + \left[\frac{\delta A_s}{A_s}\right]^2 + \left[\frac{\delta \overline{T}wi}{\theta_b}\right]^2 + \left[\frac{\delta\Phi}{\theta_b}\right]^2 + \left[\frac{\delta Tsat}{\theta_b}\right]^2\right]^{\frac{1}{2}}$$

$$\frac{\delta h}{h} = \left[[0.0142]^2 + [0.07135]^2 + \left[\frac{0.04}{7.3}\right]^2 + \left[\frac{0.025}{7.3}\right]^2 + \left[\frac{0.07}{7.3}\right]^2\right]^{\frac{1}{2}}$$

$$\frac{\delta h}{h} = 7.4 \text{ percent}$$

Table 3 shows the results of the uncertainty analysis performed. The high and low heat flux correspond to the approximate values of 1.005E+5 W/m^2 and 597 W/m^2 respectively.

TABLE 3. UNCERTAINTY ANALYSIS RESULTS

Variable	High Heat Flux	Low Heat Flux
ΔT	7.3	0.38
$\overline{T}wi$	55.17	48.04
T_{sat}	47.47	47.6
$\frac{\delta V}{V}$	1.26%	16.4%
$\frac{\delta I}{I}$	0.65%	8.3%
$\frac{\delta q}{q}$	1.42%	18.%
$\frac{\delta D_o}{D_o}$	0.707%	0.707%
$\frac{\delta L}{L}$	0.098%	0.098%
$\frac{\delta A_s}{A_s}$	0.714%	0.714%
$\frac{\delta k_{cu}}{k_{cu}}$	6.8%	6.8%
$\frac{\delta \Phi}{\Phi}$	6.96%	21.9%
$\frac{\delta h}{h}$	7.4%	22.4%

APPENDIX E: OPERATING PROCEDURES

SYSTEM LIGHT-OFF

1. Power to the 8 ton refrigeration unit is provided by the breakers located in the main distribution panel located in the laboratory. These breakers were never secured. However, if power to this panel was lost then these breakers must be reset.

2. Turn the switch on the refrigeration unit control panel, located in front of the refrigeration unit to the "auto" position after passing through "on" position. This switch is always left on, unless unit was taken down for long repairs.

2. Push the start button in the control box for the recirculation pump. This control box is located on the bulkhead above the recirculation pump in the outside area adjacent to the refrigeration unit.

3. Set the desired temperature on the roughly graduated Fahrenheit scale on the control panel thermostat. It requires approximately one hour to chill the sump 5°C. The thermometer of the ethylene glycol sump must be monitored to ensure the desired sump temperature is attained and maintained. Slight adjustments in the refrigeration unit thermostat can be expected due to the coarseness of its scale.

4. Energize the desired pumps by switching on the breakers in the main distribution power panel. Once the power is energized in the main power panel turn on the pump motors by pushing down on the arm of the appropriate breaker box for the pumps located on the bulkhead next to the ethylene glycol sump. The pumps are marked "auxiliary condenser"(Pump #2) and "instrumented tube condenser"(Pump #1), respectively in the breaker box. Flow in the auxiliary condensate system can be controlled with the individual globe valves located at the coil penetrations on the apparatus. The auxiliary condenser will produce the fastest adjustments to system pressure if pressure is

rising too quickly. Flow through the instrumented tubes can be controlled by the ball valves located at the bottom of the respective flow meter.

5. Energize the heater variacs desired by switching on the breakers (Auxiliary, Simulation, and/or Bundle) in the main distribution power panel (located near entrance of lab) and individual breakers for each of these in the power distribution box (near apparatus).

6. After ensuring that the breakers for the heater tubes desired are in the "on" position, adjust variac/s to the desired amount of heat flux. Monitor apparatus pressure through the pressure gage at the top of the apparatus, ensuring system pressure does not exceed 30 psig.

SYSTEM SHUTDOWN

1. Turn all variacs to the zero position and switch off all breakers in the power panels.

2. If apparatus will not be operated for an extended period, turn the switch on the refrigeration control panel to the "off" position after passing through "on".

3. Allow the recirculation pump to operate for at least five minutes after switching off the refrigeration unit to dissipate any back pressure in the system.

4. Turn the breakers for the pumps to the off position at the switch boxes near the ethylene glycol sump, and then secure power at the main distribution power panel.

EMERGENCY SHUTDOWN

1. Secure all power at the main distribution power panel

2. Pull fire alarm

3. Evacuate building

APPENDIX F: PROGRAM DRP4A

```
1000! FILE NAME: DRP4A
1004! DATE:      November 22, 1988
1008! REVISED:   May 1991 (S. MEMORY)
1012!
1016  BEEP
1020  PRINTER IS 1
1024  Idp=0
1028!
1032  PRINT USING "4X,""Select option default is 0:"""
1036  PRINT USING "6X,""0 Taking data or re-processing previous data"""
1040  PRINT USING "6X,""1 Plotting data on Log-Log """
1044  PRINT USING "6X,""2 Plotting data on Linear"""
1048  PRINT USING "6X,""3 Purge"""
1052  PRINT USING "6X,""4 Fixup"""
1056  PRINT USING "6X,""5 Move"""
1060  PRINT USING "6X,""6 Comb"""
1064  PRINT USING "6X,""7 Read Plot"""
1068!
1072! IDP IS A PROGRAM VARIABLE TO SELECT A SUBROUTINE
1076  INPUT Idp
1080  IF Idp=0 THEN CALL Main
1084  IF Idp=1 THEN CALL Plot
1088  IF Idp=2 THEN CALL Plin
1092  IF Idp=3 THEN CALL Purg
1096  IF Idp=4 THEN CALL Fixup
1100  IF Idp=5 THEN CALL Move
1104  IF Idp=6 THEN CALL Comb
1108  IF Idp=7 THEN CALL Readplot
1112  END
1116!
1120  SUB Main
1124! ICAL=THERMOCOUPLE CALIBRATION
1128  COM /Cc/ C(7)
1132  DIM Emf(35),T(35),D1a(6),D2a(6),Dia(6),Doa(6),La(6),Lua(6),Kcua(6),Et(19),
Ldtc(20),Volt(2),Amp(11),Twa(5),Tw(5),Theta(5),Thetab(5),Q(5),Q1(5),Qdp(5)
1136  DIM Htube(5)
1140!
1144! THERMOCOUPLE ARRAY (C( )) INITIALIZATION
1148  DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1152  DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
1156  READ C(*)
1160!
1164! PRINT HEADER AND INITIALIZE TIME CLOCK
1168  PRINTER IS 701
1172  BEEP
1176  INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Date$
1180! OUTPUT DIRECTED TO DATA AQUISITION SYSTEM (HP 3497A)
1184  OUTPUT 709;"TD";Date$
1188  OUTPUT 709;"TD"
1192  ENTER 709;Date$
1196  PRINT
1200  PRINT "           Month, date and time :";Date$
1204  PRINT
1208  PRINT USING "10X,""NOTE: Program name : DRP4"""
1212  BEEP
1216!
```

```
1220! DN IS THE VARIABLE FOR DISC NUMBER FOR RECORD KEEPING ONLY
1224  INPUT "ENTER DISK NUMBER",Dn
1228  PRINT USING "16X,""Disk number  = "",ZZ";Dn
1232  BEEP
1236  Im=0
1240  INPUT "ENTER INPUT MODE (0=3497A,1=FILE) 0=DEFAULT",Im
1244!
1248! INPUT MODE ZERO IS FROM THE DATA AQUISITION SYSTEM
1252  IF Im=0 THEN
1256      BEEP
1260      INPUT "GIVE A NAME FOR THE RAW DATA FILE",D2file$
1264      PRINT USING "16X,""File name: "",14A";D2file$
1268!
1272!     CREATE BDAT FILE ON THE MASS STORAGE MEDIA
1276      CREATE BDAT D2file$,60
1280!     CREATE AN INPUT/OUTPUT LINK TO OPEN FILES
1284      ASSIGN @File2 TO D2file$
1288!
1292!     CREATE DUMMY FILE UNTIL Nrun KNOWN
1296      D1file$="DUMMY"
1300      CREATE BDAT D1file$,60
1304      ASSIGN @File1 TO D1file$
1308      OUTPUT @File1;Date$
1312!
1316!     CREATE A PLOT FILE
1320      BEEP
1324      INPUT "GIVE A NAME FOR THE PLOT FILE",Pfile$
1328      CREATE BDAT Pfile$,30
1332      ASSIGN @Plot TO Pfile$
1336      BEEP
1340!
1344!     IDTC = NUMBER (TOTAL) OF DEFECTIVE THERMOCOUPLES
1348      INPUT "ENTER NUMBER OF DEFECTIVE TCS (0=DEFAULT)",Idtc
1352!     LDTC = LOCATION OF DEFECTIVE THERMOCOUPLE
1356!
1360      IF Idtc=0 THEN
1364          PRINT USING "16X,""No defective TCs exist"""
1368        ELSE
1372          PRINT USING "16X,""Defective Thermocouples Indicated by -99.99"""
1376      END IF
1380!
1384      BEEP
1388!     DEFECTIVE THERMOCOUPLES MAY BE IN CHANNELS 40-69
1392!     THEMOCOUPLES ARE ENTERED AS DEFECTIVE BY COMPUTER CHANNEL NO.
1396!     JDTC=COUNTER IN LOOP FOR DEFECTIVE THERMOCOUPLES
1400!
1404      IF Idtc>0 THEN
1408          FOR Jdtc=0 TO Idtc-1
1412             INPUT "ENTER DEFECTIVE TC LOCATION (BY COMPUTER CHANNEL NUMBER)
",Ldtc(Jdtc)
1416             BEEP
1420          NEXT Jdtc
1424      END IF
1428     PRINTER IS 701
1432     OUTPUT @File1;Ldtc(*)
1436 !
1440 !   Im=1 option (THIS OPTION ALLOWS DATA ENTRY WITH DATA FILE)
1444  ELSE
1448     BEEP
1452     INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D2file$
```

```
1456      PRINT USING "16X,""File name   "",14A";D2file$
1460      ASSIGN @File2 TO D2file$
1464      ENTER @File2;Nrun
1468      ENTER @File2;Dold$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
1472      BEEP
1476      INPUT "GIVE A NAME FOR PLOT FILE",Pfile$
1480      CREATE BDAT Pfile$,30
1484      ASSIGN @Plot TO Pfile$
1488      PRINT USING "16X,""This data set taken on :  "",14A";Dold$
1492      BEEP
1496      PRINTER IS 1
1500      PRINT USING "4X,""SELECT TUBE TYPE"""
1504      PRINT USING "6X,""0 SMOOTH"""
1508      PRINT USING "6X,""1 FINNED(19/IN) """
1512      PRINT USING "6X,""2 HIGH FLUX """
1516      PRINT USING "6X,""3 TURBO-B """
1520      INPUT Itt
1524   END IF
1528   IF Im=1 THEN GOTO 1768
1532   PRINTER IS 1
1536!
1540   IF Im=0 THEN
1544       PRINT USING "4X,""Select tube type"""
1548       PRINT USING "6X,"" 0  Smooth """
1552       PRINT USING "6X,"" 1  FINNED 19/IN (DEFAULT)"""
1556       PRINT USING "6X,"" 2  HIGH FLUX"""
1560       PRINT USING "6X,"" 3  TURBO-B"""
1564       PRINT USING "6X,"" 4  GROWTH"""
1568       PRINT USING "6X,"" 5  GROWTH"""
1572       PRINT USING "6X,"" 6  GROWTH"""
1576!      ITT=TUBE TYPE
1580       INPUT Itt
1584       OUTPUT @File1;Itt
1588   END IF
1592   PRINTER IS 701
1596!  Itt=2
1600   PRINT USING "16X,""Tube Type:      "",DD";Itt
1604!
1608   BEEP
1612   Bop=0
1616   INPUT "ENTER BULK OIL %  (DEFAULT=0%) ",Bop
1620   OUTPUT @File1;Bop
1624   PRINT USING "16X,""Bulk oil%="",DD";Bop
1628!
1632   BEEP
1636!  NHT=NUMBER OF HEATED TUBES
1640   Nht=5
1644   INPUT "Enter number of heated instrumented tubes(default=5)",Nht
1648   OUTPUT @File1;Nht
1652   PRINT USING "16X,""Number of heated instrumented tubes="",DD";Nht
1656   BEEP
1660!
1664!  Natp=Number of active dummy pairs
1668   Natp=0
1672   INPUT "Enter number of active dummy pairs (Default=0)",Natp
1676   OUTPUT @File1;Natp
1680   PRINT USING "16X,""Number of active dummy pairs="",DD";Natp
1684   BEEP
1688!
1692!  NRT=NUMBER OF ADDED HEATED TUBES TO ENHANCE BUNDLE EFFECT
```

```
1696  Nrt=0
1700  INPUT "Enter number of added heated tubes from simulation heaters(Default=
0)",Nrt
1704  OUTPUT @File1;Nrt
1708  PRINT USING "16X,""Number of added heated tubes(from simulation heaters)="
",DD";Nrt
1712  BEEP
1716!
1720! CORR IS CORRECTION FOR INSTRUMENTED TUBE HEIGHT
1724  Corr=0
1728  INPUT "WANT TO CORRECT TSAT FOR TUBE HEIGHT (0=YES(DEFAULT),1=NO)",Corr
1732        IF Corr=0 THEN PRINT USING "16X,""TSAT is corrected instrumented heat
ed tube height"""
1736        IF Corr=1 THEN PRINT USING "16X,""TSAT is NOT corrected for instrumen
ted heated tube height"""
1740  OUTPUT @File1;Corr
1744  BEEP
1748! ILQV=INPUT MODE: LIQUID, VAPOR,OR LIQUID VAPOR AVERAGE
1752  Ilqv=0
1756  INPUT "SELECT (0=LIQ(default),1=VAP,2=(LIQ+VAP)/2)",Ilqv
1760!
1764! D1A=Diameter at thermocouple positions (meters)
1768  DATA .0122,0.0098,0.0106,0.0116,0,0,0
1772  READ D1a(*)
1776  D1=D1a(Itt)
1780!
1784! D2=Diameter to base of fins (outside dia for smooth)(meters)
1788  DATA .0158,0.0125,0.0158,0.01415,0,0,0
1792  READ D2a(*)
1796  D2=D2a(Itt)
1800!
1804! Di=Inside diameter of unenhanced ends (meters)
1808  DATA .0132,0.0109,0.0116,0.0127,0,0,0
1812  READ Dia(*)
1816  Di=Dia(Itt)
1820!
1824! Do=Outside diameter of unenhanced ends (meters)
1828  DATA .015875,0.0125,0.015875,0.01415,0,0,0
1832  READ Doa(*)
1836  Do=Doa(Itt)
1840!
1844! L=Length of enhanced surface (meters)
1848  DATA .2032,.2032,.2032,.2032,.2032,.2032,.2032
1852  READ La(*)
1856  L=La(Itt)
1860!
1864! Lu=CORRECTED Length of unenhanced surface at the ends (METERS)
1868!LU=LFIN + THICKNESS/2
1872  DATA .0261,.0254,.0264,0.0258,0,0,0
1876  READ Lua(*)
1880  Lu=Lua(Itt)
1884!
1888! LV=corrected length of 3 inch finned like end
1892  DIM Lva(6)
1896  DATA .0769,.0762,.0773,0.0766,0,0,0
1900  READ Lva(*)
1904  Lv=Lva(Itt)
1908! Kcua=Thermal Conductivity of tube
1912! DATA 401,0,0,0,0,0,0
1916! READ Kcua(*)
```

```
1920! Kcu=Kcua(Itt)
1924  A=PI*(Do^2-Di^2)/4
1928  P=PI*Do
1932  J=1
1936  Sx=0
1940  Sy=0
1944  Sxs=0
1948  Sxy=0
1952 Repeat: !
1956!
1960  IF Im=0 THEN
1964!     Dtld=desired temperature of liquid
1968      Dtld=47.5      !R-113
1969!     Dtld=2.2       !R-114
1972      Ido=2
1976      ON KEY 0,15 RECOVER 1952
1980      PRINTER IS 1
1984      PRINT USING "4X,""SELECT OPTION """
1988      PRINT USING "6X,""0=TAKE DATA"""
1992      PRINT USING "6X,""1=SET HEAT FLUX"""
1996      PRINT USING "6X,""2=SET Tsat (DEFAULT SET FOR R-113)"""
2000      PRINT USING "4X,""NOTE: KEY 0 = ESCAPE"""
2004!     Ido=desired option
2008      BEEP
2012      INPUT Ido
2016!
2020      BEEP
2024!     Set default value for input
2028      IF Ido>2 THEN Ido=2
2032!     Take data option
2036      IF Ido=0 THEN 2440
2040!
2044! LOOP TO SET HEAT FLUX  (FOR TOP INSTRUMENTED TUBE)
2048      IF Ido=1 THEN
2052      Dqdp=100000
2056           PRINT USING "4X,""Qdp            QDPsim        Nrt       Qdpaux
 Qtot"""
2060           PRINT USING "4X,""(W/m^2)       (W/m^2)                   (W/m^2)
 (W)"""
2064           Err=1
2068!          Reset,read channel 25-30,automatic scaling
2072!          Channel 25=aux amps,26=sim amps,27=inst volts,28=sim volts,29=aux
 volts,30=inst amps
2076           OUTPUT 709;"AR AF25 AL30 VRS"
2080           FOR I=10 TO 11
2084               OUTPUT 709;"AS SA"
2088               ENTER 709;Amp(I)
2092           NEXT I
2096           FOR I=0 TO 2
2100               OUTPUT 709;"AS SA"
2104               ENTER 709;Volt(I)
2108           NEXT I
2112           OUTPUT 709;"AS SA"
2116           ENTER 709;Amp(0)
2120!          Calculate actual heat flux
2124           Q(0)=60*Volt(0)*Amp(0)
2128           Qdp(0)=Q(0)/(PI*D2*L)
2132           Qsim=60*20*Volt(1)*Amp(11)
2136           Qdpsim=Qsim/(PI*D2*.2032*3)
2140           Qaux=60*20*Volt(2)*Amp(10)
```

```
2144          Qdpaux=Qaux/(PI*.0160*.1778*4)
2148          Qtot=Q(0)*Nht+Qsim+Qaux
2152          Nrt=Qdpsim/Qdp(0)
2156          IF ABS(Aqdp-Dqdp)>Err THEN
2160              IF Aqdp>Dqdp THEN
2164                  BEEP 4000,.2
2168              ELSE
2172                  BEEP 250,.2
2176              END IF
2180              IF Nrt<.1 THEN Nrt=0
2184              IF Qdpaux<100 THEN Qdpaux=0
2188              IF Qdpsim<100 THEN Qdpsim=0
2192              PRINT USING "4X,2(MZ.3DE,2X),2X,(MDD.DD),2X,2(MZ.3DE,2X)";Qdp
(0),Qdpsim,Nrt,Qdpaux,Qtot
2196              WAIT 2
2200              GOTO 2076
2204          END IF
2208      END IF
2212!
2216!     LOOP TO SET Tsat
2220      IF Ido=2 THEN
2224          IF Ikdt=1 THEN 2240
2228              BEEP
2232              INPUT "ENTER DESIRED Tsat (DEFAULT=47.5 C - R-113)",Dtld
2233!             INPUT "ENTER DESIRED Tsat (DEFAULT=2.2 C - R-114)",Dtld
2236              Ikdt=1
2240              Old1=0
2244              Old2=0
2248              Nn=1
2252              Nrs=Nn MOD 15
2256              Nn=Nn+1
2260              IF Nrs=1 THEN
2264                  PRINT USING "4X,""  DTsat       Tld1       Tld2       Tlbb
    Tvat       Tvab       Tlav    """
2268              END IF
2272!             Read thermocouple voltages for vapor, liquid
2276              OUTPUT 709;"AR AF0 AL5 VR5"
2280!             Sample each thermocouple 20 times and report temp for each the
rmocouple, vapor=0,1,2;  liquid=3&4
2284              FOR I=0 TO 5
2288                  Sum=0
2292                  OUTPUT 709;"AS SA"
2296                  FOR Ji=1 TO 20
2300                      ENTER 709;Eliq
2304                      Sum=Sum+Eliq
2308                  NEXT Ji
2312                  Emf(I)=Sum/20
2316                  T(I)=FNTvsv(Emf(I))
2320              NEXT I
2324!         Compute average temperature of liquid
2328          Tlav=(T(3)+T(4))*.5
2332!         Compute average temperature of vapor
2333          Tvav1=(T(0)+T(1))/2
2334          Tvav2=T(2)
2336          Tvav=(T(0)+T(1)+T(2))/3
2340          IF ABS(Tlav-Dtld)>.2 THEN
2344              IF Tlav>Dtld THEN
2348                  BEEP 4000,.2
2352              ELSE
2356                  BEEP 250,.2
```

```
2360                END IF
2364            ELSE
2368                IF ABS(Tlav-Dtld)>.1 THEN
2372                     IF Atld>Dtld THEN
2376                          BEEP 3000,.2
2380                     ELSE
2384                          BEEP 800,.2
2388                     END IF
2392                END IF
2396            END IF
2400            Err1=Tlav-Old1
2404            Old1=Tlav
2408            Err2=Tvav-Old2
2412            Old2=Tvav
2416            PRINT USING "4X,7(MDDD.DD,3X)";Dtld,T(3),T(4),T(5),Tvav1,Tvav2,Tla
v
2420            WAIT 2
2424            GOTO 2252
2428        END IF
2432!
2436!       TAKE DATA IF Im=0 LOOP
2440        IF Ikol=1 THEN 2452
2444            BEEP
2448            Ikol=1
2452            OUTPUT 709;"AR AF0 AL5 VR5"
2456            FOR I=0 TO 5
2460                OUTPUT 709;"AS SA"
2464                Sum=0
2468                FOR J1=1 TO 20
2472                    ENTER 709;E
2476                    Sum=Sum+E
2480                    IF I>2 THEN Et(J1-1)=E
2484                NEXT J1
2488                Kdl=0
2492                IF I>2 THEN
2496                    Eave=Sum/20
2500                    Sum=0.
2504                    FOR Jk=0 TO 19
2508                        IF ABS(Et(Jk)-Eave)<5.0E-6 THEN
2512                             Sum=Sum+Et(Jk)
2516                        ELSE
2520                             Kdl=Kdl+1
2524                        END IF
2528                    NEXT Jk
2532                    IF I>2 THEN PRINT USING "4X,""Kdl = "",DD";Kdl
2536                        IF Kdl>10 THEN
2540                            BEEP
2544                            BEEP
2548                            PRINT USING "4X,""Too much scattering in data - re
peat data set"""
2552                            GOTO 1980
2556                        END IF
2560                    END IF
2564                Emf(I)=Sum/(20-Kdl)
2568            NEXT I
2572            OUTPUT 709;"AR AF40 AL69 VR5"
2576            FOR I=6 TO 35
2580                OUTPUT 709;"AS SA"
2584                Sum=0
2588                FOR J1=1 TO 5
```

```
2592                 ENTER 709;E
2596                 Sum=Sum+E
2600             NEXT J1
2604             Emf(I)=Sum/5
2608         NEXT I
2612!
2616!        READ VOLTAGES (27=Inst,28=Sim,29=Aux)
2620         OUTPUT 709;"AR AF27 AL29 VR5"
2624         FOR I=0 TO 2
2628             OUTPUT 709;"AS SA"
2632             ENTER 709;Volt(I)
2636         NEXT I
2640!
2644!        READ CURRENTS (30-34=Inst tubes;35-39=ACTIVE Dummy)
2648         OUTPUT 709;"AR AF30 AL39 VR5"
2652         FOR I=0 TO 9
2656             OUTPUT 709;"AS SA"
2660             ENTER 709;Amp(I)
2664         NEXT I
2668!    Read Currents(25=Aux amps,26=Sim amps)
2672         OUTPUT 709;"AR AF25 AL26 VR5"
2676         FOR I=10 TO 11
2680             OUTPUT 709;"AS SA"
2684             ENTER 709;Amp(I)
2688         NEXT I
2692         ELSE
2696         ENTER @File2;Emf(*),Volt(*),Amp(*)
2700     END IF
2704!
2708!    CONVERT EMF'S TO TEMP,VOLT,CURRENT
2712     FOR I=0 TO 35
2716         T(I)=FNTvsv(Emf(I))
2720         IF I>5 AND Idtc>0 THEN
2724             FOR I1=0 TO Idtc-1
2728                 IF Ldtc(I1)=I-5+39 THEN T(I)=-99.99
2732             NEXT I1
2736         END IF
2740     NEXT I
2744!    Ntc=nr of thermocouples
2748     Ntc=6
2752     FOR I1=0 TO 4
2756         Q(I1)=60*Volt(0)*Amp(I1)
2760!        Twa=Average temperature of the wall
2764         Twa(I1)=0
2768         Ndtc=0
2772         FOR I=1 TO Ntc
2776!            Nn is counter in temp array, start at 6 (this is the  first th
ermocouple in the tube bank)
2780             Nn=I1*6+I+5
2784             IF ABS(T(Nn)) 99 THEN
2788                 T(Nn)=-99.99
2792                 Ndtc=Ndtc+1
2796             ELSE
2800                 Twa(I1)=Twa(I1)+T(Nn)
2804             END IF
2808         NEXT I
2812         Twa(I1)=Twa(I1)/(6-Ndtc)
2816     NEXT I1
2820     Tlav=(T(3)+T(4))/2
2821     Tvav=T(2)
```

```
2824!     Tvav=(T(0)+T(1)+T(2))/3
2828!
2829!     Tlav=T(5)
2832      Tcu=Twa(0)
2836      Kcu=FNKcu(Tcu)        !THERMAL CONDUCTIVITY OF COPPER
2840!                           !IF CURVE FIT NOT AVAIL USE ARRAY KCU(*)
2844! FOURIER CONDUCTION EQUATION WITH CONTACT RESISTANCE NEGLECTED
2848      FOR I=0 TO 4
2852          Tw(I)=Twa(I)-Q(I)*LOG(D2/D1)/(2*PI*Kcu*L)
2856          IF Ilqv=0 THEN Texs=Tlav
2860          IF Ilqv=1 THEN Texs=Tvav
2864          IF Ilqv=2 THEN Texs=(Tlav+T(2))*.5
2868          IF Corr=1 THEN Thetab(I)=Tw(I)-Texs
2872!         IF Corr=0 THEN Thetab(I)=Tw(I)-(Texs+.056+I*.129)  !R-114
2876          IF Corr=0 THEN Thetab(I)=Tw(I)-(Texs+.054+I*.144)  !R-113
2880      NEXT I
2884!
2888!     COMPUTE VARIOUS PROPERTIES
2892      Tfilm=(Tw(0)+Texs)*.5  !FILM TEMPERATURE
2896      Rho=FNRho(Tfilm)       !DENSITY
2900      Mu=FNMu(Tfilm)         !VISCOSITY
2904      K=FNK(Tfilm)           !THERMAL CONDUCTIVITY
2908      Cp=FNCp(Tfilm)         !SPECIFIC HEAT
2912      Beta=FNBeta(Tfilm)     !THERMAL EXPANSION
2916      Ni=Mu/Rho              !KINEMATIC VISCOSITY
2920      Alpha=K/(Rho*Cp)       !THERMAL DIFFUSIVITY
2924      Pr=Ni/Alpha            !PRANDTL
2928!
2932!     COMPUTE NATURAL-CONVECTIVE HEAT-TRANSFER COEFFICIENT
2936!     FOR UNENHANCED END(S)
2940      Lu=Lua(Itt)
2944      Hbar=190
2948      Fe=(Hbar*P/(Kcu*A))^.5*Lu
2952      Tanh=FNTanh(Fe)
2956      Theta(0)=Thetab(0)*Tanh/Fe
2960      Xx=(9.81*Beta*Thetab(0)*Do^3*Tanh/(Fe*Ni*Alpha))^.166667
2964      Yy=(1+(.559/Pr)^(9/16))^(8/27)
2968      Hbarc=K/Do*(.6+.387*Xx/Yy)^2
2972      IF ABS((Hbar-Hbarc)/Hbarc)>.001 THEN
2976          Hbar=(Hbar+Hbarc)*.5
2980          GOTO 2948
2984      END IF
2988!
2992!     COMPUTE HEAT LOSS RATE THROUGH UNENHANCED END(S)
2996      Q1(0)=(Thetab(0)*Tanh)*((Hbar*P*Kcu*A)^.5)
3000      Qq=Q1(0)+Qq
3004      Z=Z+1
3008      IF Z=1 THEN
3012         Lu=Lv
3016         GOTO 2944
3020      END IF
3024      Z=0
3028      Q1pct=Qq/Q(0)
3032      Qq=0
3036      As=PI*D2*L
3040      FOR I1=0 TO 4
3044          Q1(I1)=Q1pct*Q(I1)
3048          Qdp(I1)=(Q(I1)-Q1(I1))/As
3052          Htube(I1)=Qdp(I1)/Thetab(I1)
3056      NEXT I1
```

```
3060      PRINTER IS 701
3064!
3068!     RECORD TIME OF DATA TAKING
3072      IF Im=0 THEN
3076          OUTPUT 709;"TD"
3080          ENTER 709;Told$
3084      END IF
3088!
3092!     OUTPUT DATA TO PRINTER
3096      PRINTER IS 701
3100      PRINT
3104      PRINT USING "10X,""Data Set Number = "",DDD,2X,14A";J,Told$
3108      PRINT
3112      PRINT USING "10X,""  Tv1      Tv2      Tv3      Tld1     Tld2     Tld3
Tvav     Tldav """
3116      PRINT USING "10X,8(MDD.DD,2X)";T(0),T(1),T(2),T(3),T(4),T(5),Tvav,Tlav
3120      PRINT
3124      PRINT USING "6X,""Tube     Wall Temperatures (Deg C)      Tnave      Qdp
     H         Thetab"""
3128      PRINT USING "6X,""#    1     2     3     4     5     6  (Deg C)  (W/m^
2)  (W/m^2.K)   (K)"""
3132      Jj=0
3136      FOR I1=0 TO Nht-1
3140          FOR J1=0 TO 5
3144              Tp(J1)=T(I1*5+Jj+6)
3148              Jj=Jj+1
3152          NEXT J1
3156          Jj=I1+1
3160          FOR J1=0 TO 4
3164               Tn(J1)=1+J1
3168          NEXT J1
3172          PRINT USING "6X,D,1X,7(MDD.DD),1X,2(MZ.3DE),1X,1(MDD.DD)";Tn(I1),T
p(0),Tp(1),Tp(2),Tp(3),Tp(4),Tp(5),Twa(I1),Qdp(I1),Htube(I1),Thetab(I1)
3176      NEXT I1
3180      Ok=1
3184      IF Im=0 THEN
3188          BEEP
3192          INPUT "OK TO STORE THIS DATA SET (1=Y(default),0=N)?",Ok
3196      END IF
3200!     J=the counter for data sets
3204      IF Ok=1 OR Im=1 THEN J=J+1
3208      IF Ok=1 AND Im=0 THEN OUTPUT @File1;Emf(*),Volt(*),Amp(*)
3212      IF Im=1 OR Ok=1 THEN OUTPUT @Plot;Qdp(*),Htube(*),Thetab(*)
3216      Go_on=1
3220      IF Im=0 THEN
3224          BEEP
3228          INPUT "WILL THERE BE ANOTHER RUN (1=Y(default),0=N)?",Go_on
3232          Nrun=J
3236      IF Go_on=0 THEN 3272
3240      IF Go_on<>0 THEN Repeat
3244      ELSE
3248      IF J<Nrun+1 THEN Repeat
3252      END IF
3256      St=1
3260      BEEP
3264      INPUT "ARE YOU SURE YOUR READY TO TERMINATE (1=Y(DEFAULT),0=NO)?",St
3268      Go_on=1
3272      IF St>0 THEN 3280
3276      IF St=0 THEN GOTO 3240
3280      IF Im=0 THEN
```

```
3284            BEEP
3288            PRINT
3292            PRINT USING "10X,""NOTE: "",ZZ,"" data runs were stored in file ""
,10A";J-1,D2file$
3296            ASSIGN @File1 TO *
3300            OUTPUT @File2;Nrun-1
3304            ASSIGN @File1 TO D1file$
3308            ENTER @File1;Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
3312            OUTPUT @File2;Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
3316            FOR I=1 TO Nrun-1
3320                ENTER @File1;Emf(*),Volt(*),Amp(*)
3324                OUTPUT @File2;Emf(*),Volt(*),Amp(*)
3328            NEXT I
3332            ASSIGN @File1 TO *
3336            PURGE "DUMMY"
3340        END IF
3344        BEEP
3348        PRINT
3352        PRINT USING "10X,""NOTE: "",ZZ,"" X-Y pairs were stored in plot data f
ile "",10A";J-1,Pfile$
3356        ASSIGN @File2 TO *
3360        ASSIGN @Plot TO *
3364        BEEP
3368    SUBEND
3372!
3376!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
3380!
3384    DEF FNKcu(Tcu)
3388!   OFHC COPPER
3392    Tk=Tcu+273.15       !C TO K
3396!   Kcu=434-.112*Tk      !250-300K USE FOR R-114 @2.2 C
3400    Kcu=433.0-.1*Tk      !200-400K USE FOR R-113 @47.5 C
3404    RETURN Kcu
3408    FNEND
3412!
3416    DEF FNMu(T)
3420!   CURVE FIT OF VISCOSITY
3424    Tk=T+273.15       !C TO K
3428!   Mu=EXP(-4.4636+(1011.47/Tk))*1.0E-3   !R-114 170-360 K
3432    Mu=.0000134*(10^(503/(Tk-2.15)))     !R113
3436    RETURN Mu
3440    FNEND
3444!
3448    DEF FNCp(T)
3452!   CURVE FIT OF Cp
3456    Tk=T+273.15       !C TO K
3460!   Cp=.40188+1.65007E-3*Tk+1.51494E-6*Tk^2-6.67853E-10*Tk^3 !R-114 180-400 K
3464    Cp=(929+1.03*T)*.001    !R-113
3468    Cp=Cp*1000
3472    RETURN Cp
3476    FNEND
3480!
3484    DEF FNRho(T)
3488    Tk=T+273.15       !C TO K
3492    X=1-(1.8*Tk/753.95)  !K TO R
3496!   Ro=36.32+61.146414*X^(1/3)+16.418015*X+17.476838*X^.5+1.119828*X^2
3500!   Ro=Ro/.062428       !R-114
3504    Ro=1.6207479E+3-T*(2.2186346+T*2.3578291E-3)      !R-113
3508    RETURN Ro
3512    FNEND
```

```
3516!
3520 DEF FNPr(T)    !GOOD FOR R-114/R-113
3524 Pr=FNCp(T)*FNMu(T)/FNK(T)
3528 RETURN Pr
3532 FNEND
3536!
3540 DEF FNK(T)
3544! T<360 K WITH T IN C
3548 K=.071-.000261*T
3552 RETURN K
3556 FNEND
3560!
3564 DEF FNTanh(Fe)
3568 P=EXP(Fe)
3572 Q=EXP(-Fe)
3576 Tanh=(P-Q)/(P+Q)
3580 RETURN Tanh
3584 FNEND
3588!
3592 DEF FNTvsv(V)
3596 COM /Cc/ C(7)
3600 T=C(0)
3604 FOR I=1 TO 7
3608 T=T+C(I)*V^I
3612 NEXT I
3616 RETURN T
3620 FNEND
3624!
3628 DEF FNBeta(T)
3632 Rop=FNRho(T+.1)
3636 Rom=FNRho(T-.1)
3640 Beta=-2/(Rop+Rom)*(Rop-Rom)/.2
3644 RETURN Beta
3648 FNEND
3652 DEF FNPoly(X)
3656 COM /Cply/ A(10,10),C(10),B(4),Nop,Iprnt,Opo,Ilog
3660 X1=X
3664 Poly=B(0)
3668 FOR I=1 TO Nop
3672     IF Ilog=1 THEN X1=LOG(X)
3676     Poly=Poly+B(I)*X1^I
3680 NEXT I
3684 IF Ilog=1 THEN Poly=EXP(Poly)
3688 RETURN Poly
3692 FNEND
3696!
3700!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
3704!
3708 SUB Poly(Dfile$(*),Np,Itn)
3712 DIM R(10),S(10),Sy(12),Sx(12),Xx(100),Yy(100),Xy(17)
3716 COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
3720 COM /Xxyy/ Xp(5),Yp(5)
3724 FOR I=0 TO 4
3728 B(I)=0
3732 NEXT I
3736 Im=1
3740 BEEP
3744 INPUT "ENTER DATA FILE NAME",Dfile$(0)
3748 BEEP
3752 INPUT "ENTER NUMBER OF X-Y PAIRS",Np
```

```
3756  BEEP
3760  INPUT "LIKE TO EXCLUDE DATA PAIRS (1=Y,0=N(DEFAULT))?",Ied
3764  IF Ied=1 THEN
3768     BEEP
3772     INPUT "ENTER NUMBER OF PAIRS TO BE EXCLUDED",Ipex
3776  END IF
3780  ASSIGN @File TO Dfile$(0)
3784  N=2
3788  BEEP
3792  INPUT "ENTER THE ORDER OF POLYNOMIAL (DEFAULT=2) ",N
3796  FOR I=0 TO N
3800      Sy(I)=0
3804      Sx(I)=0
3808  NEXT I
3812  IF Ied=1 AND Im=1 THEN
3816     FOR I=1 TO Ipex
3820         ENTER @File;Xy(*)
3824     NEXT I
3828  END IF
3832  FOR I=1 TO Np-Ipex
3836      ENTER @File;Xy(*)
3840      IF Opo=0 THEN
3844         Y=Xy(Itn-1)
3848         X=Xy(11+Itn)
3852      END IF
3856      IF Opo=1 THEN
3860         Y=Xy(5+Itn)
3864         X=Xy(11+Itn)
3868      END IF
3872      IF Opo=2 THEN
3876         Y=Xy(5+Itn)
3880         X=Xy(Itn-1)
3884      END IF
3888      IF Ilog=1 THEN
3892         X=LOG(X)
3896         Y=LOG(Y)
3900      END IF
3904      Xx(I)=X
3908      Yy(I)=Y
3912      R(0)=Y
3916      Sy(0)=Sy(0)+Y
3920      S(1)=X
3924      Sx(1)=Sx(1)+X
3928      FOR J=1 TO N
3932          R(J)=R(J-1)*X
3936          Sy(J)=Sy(J)+R(J)
3940      NEXT J
3944      FOR J=2 TO N*2
3948          S(J)=S(J-1)*X
3952          Sx(J)=Sx(J)+S(J)
3956      NEXT J
3960  NEXT I
3964  Sx(0)=Np
3968  FOR I=0 TO N
3972      C(I)=Sy(I)
3976      FOR J=0 TO N
3980          A(I,J)=Sx(I+J)
3984      NEXT J
3988  NEXT I
3992  FOR I=0 TO N-1
```

```
3996      CALL Divide(I)
4000      CALL Subtract(I+1)
4004  NEXT I
4008  B(N)=C(N)/A(N,N)
4012  FOR I=0 TO N-1
4016      B(N-1-I)=C(N-1-I)
4020      FOR J=0 TO I
4024          B(N-1-I)=B(N-1-I)-A(N-1-I,N-J)*B(N-J)
4028      NEXT J
4032      B(N-1-I)=B(N-1-I)/A(N-1-I,N-1-I)
4036  NEXT I
4040  IF Iprnt=0 THEN
4044     PRINT USING "12X,""EXPONENT    COEFFICIENT"""
4048     FOR I=0 TO N
4052         PRINT USING "15X,DD,5X,MD.7DE";I,B(I)
4056     NEXT I
4060     PRINT " "
4064     PRINT USING "12X,""DATA POINT      X              Y       Y(CALCULATED) DI
SCREPANCY"""
4068     FOR I=1 TO Np
4072         Yc=B(0)
4076         FOR J=1 TO N
4080             Yc=Yc+B(J)*Xx(I)^J
4084         NEXT J
4088         D=Yy(I)-Yc
4092         PRINT USING "15X,3D,4X,4(MD.5DE,1X)";I,Xx(I),Yy(I),Yc,D
4096      NEXT I
4100  END IF
4104  ASSIGN @File TO *
4108  SUBEND
4112!
4116  SUB Divide(M)
4120  COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
4124  FOR I=M TO N
4128      Ao=A(I,M)
4132      FOR J=M TO N
4136          A(I,J)=A(I,J)/Ao
4140      NEXT J
4144      C(I)=C(I)/Ao
4148  NEXT I
4152  SUBEND
4156!
4160  SUB Subtract(K)
4164  COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
4168  FOR I=K TO N
4172      FOR J=K-1 TO N
4176          A(I,J)=A(K-1,J)-A(I,J)
4180      NEXT J
4184      C(I)=C(K-1)-C(I)
4188  NEXT I
4192  SUBEND
4196!
4200  SUB Plin
4204  COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
4208  COM /Xxyy/ Xx(5),Yy(5)
4212  PRINTER IS 705
4216  BEEP
4220  INPUT "SELECT (0=h/h0% same tube,1=h(HF)/h(sm)",Irt
4224  BEEP
4228  INPUT "WHICH Tsat (1=6.7,0=-2.2)",Isat
```

```
4232  Xmin=0
4236  Xmax=10
4240  Xstep=2
4244  IF Irt=0 THEN
4248     Ymin=0
4252     Ymax=1.4
4256     Ystep=.2
4260     ELSE
4264     Ymin=0
4268     Ymax=15
4272     Ystep=5
4276  END IF
4280  BEEP
4284  PRINT "IN;SP1;IP 2300,2200,8300,6800;"
4288  PRINT "SC 0,100,0,100;TL 2,0;"
4292  Sfx=100/(Xmax-Xmin)
4296  Sfy=100/(Ymax-Ymin)
4300  PRINT "PU 0,0 PD"
4304  FOR Xa=Xmin TO Xmax STEP Xstep
4308      X=(Xa-Xmin)*Sfx
4312      PRINT "PA";X,",0; XT;"
4316  NEXT Xa
4320  PRINT "PA 100,0;PU;"
4324  PRINT "PU PA 0,0 PD"
4328  FOR Ya=Ymin TO Ymax STEP Ystep
4332      Y=(Ya-Ymin)*Sfy
4336      PRINT "PA 0,";Y,"YT"
4340  NEXT Ya
4344  PRINT "PA 0,100 TL 0 2"
4348  FOR Xa=Xmin TO Xmax STEP Xstep
4352      X=(Xa-Xmin)*Sfx
4356      PRINT "PA";X,",100; XT"
4360  NEXT Xa
4364  PRINT "PA 100,100 PU PA 100,0 PD"
4368  FOR Ya=Ymin TO Ymax STEP Ystep
4372      Y=(Ya-Ymin)*Sfy
4376      PRINT "PD PA 100,",Y,"YT"
4380  NEXT Ya
4384  PRINT "PA 100,100 PU"
4388  PRINT "PA 0,-2 SR 1.5,2"
4392  FOR Xa=Xmin TO Xmax STEP Xstep
4396      X=(Xa-Xmin)*Sfx
4400      PRINT "PA";X,",0;"
4404      PRINT "CP -2,-1;LB";Xa;""
4408  NEXT Xa
4412  PRINT "PU PA 0,0"
4416  FOR Ya=Ymin TO Ymax STEP Ystep
4420      IF ABS(Ya)<1.E-5 THEN Ya=0
4424      Y=(Ya-Ymin)*Sfy
4428      PRINT "PA 0,";Y,""
4432      PRINT "CP -4,-.25;LB";Ya;""
4436  NEXT Ya
4440  Xlabel$="Oil Percent"
4444  IF Irt=0 THEN
4448     Ylabel$="h/h0%"
4452     ELSE
4456     Ylabel$="h/hsmooth"
4460  END IF
4464  PRINT "SR 1.5,2;PU PA 50,-10 CP";-LEN(Xlabel$)/2;"0;LB";Xlabel$;""
4468  PRINT "PA -11,50 CP 0,";-LEN(Ylabel$)/2*5/6;"DI 0,1;LB";Ylabel$;""
```

```
4472  PRINT "CP 0,0"
4476  Ipn=0
4480  BEEP
4484  INPUT "WANT TO PLOT DATA FROM A FILE (1=Y,0=N)?",Okp
4488  Icn=0
4492  IF Okp=1 THEN
4496  BEEP
4500  INPUT "ENTER THE NAME OF THE DATA FILE",D_file$
4504  BEEP
4508  INPUT "SELECT (0=LINEAR, 1=LOG(X,Y)",Ilog
4512  ASSIGN @File TO D_file$
4516  BEEP
4520  INPUT "ENTER THE BEGINNING RUN NUMBER",Md
4524  BEEP
4528  INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED",Npairs
4532  BEEP
4536  INPUT "ENTER DESIRED HEAT FLUX",Q
4540  BEEP
4544  PRINTER IS 1
4548  PRINT USING "4X,""Select a symbol:"""
4552  PRINT USING "4X,""1  Star    2  Plus sign"""
4556  PRINT USING "4X,""3  Circle 4  Square"""
4560  PRINT USING "4X,""5  Rombus"""
4564  PRINT USING "4X,""6  Right-side-up triangle"""
4568  PRINT USING "4X,""7  Up-side-down triangle"""
4572  INPUT Sym
4576  PRINTER IS 705
4580  PRINT "PU DI"
4584  IF Sym=1 THEN PRINT "SM*"
4588  IF Sym=2 THEN PRINT "SM+"
4592  IF Sym=3 THEN PRINT "SMo"
4596  Nn=4
4600  IF Ilog=1 THEN Nn=1
4604  IF Md>1 THEN
4608     FOR I=1 TO (Md-1)
4612         ENTER @File;Xa,Ya
4616     NEXT I
4620  END IF
4624  Q1=Q
4628  IF Ilog=1 THEN Q=LOG(Q)
4632  FOR I=1 TO Npairs
4636      ENTER @File;Xa,B(*)
4640      Ya=B(0)
4644      FOR K=1 TO Nn
4648          Ya=Ya+B(K)*Q^K
4652      NEXT K
4656      IF Ilog=1 THEN Ya=EXP(Ya)
4660      IF Ilog=0 THEN Ya=Q1/Ya
4664      IF Irt=0 THEN
4668         IF Xa=0 THEN
4672            Yo=Ya
4676            Ya=1
4680            ELSE
4684            Ya=Ya/Yo
4688         END IF
4692         ELSE
4696         Hsm=FNHsmooth(Q,Xa,Isat)
4700         Ya=Ya/Hsm
4704      END IF
4708  Xx(I-1)=Xa
```

```
4712  Yy(I-1)=Ya
4716  X=(Xa-Xmin)*Sfx
4720  Y=(Ya-Ymin)*Sfy
4724  IF Sym>3 THEN PRINT "SM"
4729  IF Sym<4 THEN PRINT "SR 1.4,2.4"
4732  PRINT "PA",X,Y,""
4736  IF Sym>3 THEN PRINT "SR 1.2,1.6"
4740  IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0;"
4744  IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6;"
4749  IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,8;"
4752  IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8;"
4756  NEXT I
4760  BEEP
4764  ASSIGN @File TO *
4768  END IF
4772  PRINT "PU SM"
4776  BEEP
4780  INPUT "WANT TO PLOT A POLYNOMIAL (1=Y,0=N)?",Okp
4784  IF Okp=1 THEN
4788     BEEP
4792     INPUT "SELECT (0=LINEAR,1=LOG(X,Y))",Ilog
4796     Iprnt=1
4800     CALL Poly(Itn)
4804     FOR Xa=Xmin TO Xmax STEP Xstep/25
4808         Icn=Icn+1
4812         Ya=FNPoly(Xa)
4816         Y=(Ya-Ymin)*Sfy
4820         X=(Xa-Xmin)*Sfx
4824         IF Y<0 THEN Y=0
4828         IF Y>100 THEN GOTO 4868
4832         Pu=0
4836         IF Ipn=1 THEN Idf=Icn MOD 2
4840         IF Ipn=2 THEN Idf=Icn MOD 4
4844         IF Ipn=3 THEN Idf=Icn MOD 8
4848         IF Ipn=4 THEN Idf=Icn MOD 16
4852         IF Ipn=5 THEN Idf=Icn MOD 32
4856         IF Idf=1 THEN Pu=1
4860         IF Pu=0 THEN PRINT "PA",X,Y,"PD"
4864         IF Pu=1 THEN PRINT "PA",X,Y,"PU"
4868     NEXT Xa
4872     PRINT "PU"
4876     Ipn=Ipn+1
4880     GOTO 4480
4884  END IF
4888  BEEP
4892  INPUT "WANT TO QUIT (1=Y,0=N)?",Iquit
4896  IF Iquit=1 THEN 4904
4900  GOTO 4480
4904  PRINT "PU SP0"
4908  SUBEND
4912  SUB Stats
4916  PRINTER IS 701
4920  J=0
4924  K=0
4929  BEEP
4932  INPUT "PLOT FILE TO ANALYZE?",File$
4936  ASSIGN @File TO File$
4940  BEEP
4944  INPUT "LAST RUN No?(0=QUIT)",Nn
4948  IF Nn=0 THEN 5092
```

```
4952  Nn=Nn-J
4956  Sx=0
4960  Sy=0
4964  Sz=0
4968  Sxs=0
4972  Sys=0
4976  Szs=0
4980  FOR I=1 TO Nn
4984  J=J+1
4988  ENTER @File;Q,T
4992  H=Q/T
4996  Sx=Sx+Q
5000  Sxs=Sxs+Q^2
5004  Sy=Sy+T
5008  Sys=Sys+T^2
5012  Sz=Sz+H
5016  Szs=Szs+H^2
5020  NEXT I
5024  Qave=Sx/Nn
5028  Tave=Sy/Nn
5032  Have=Sz/Nn
5036  Sdevq=SQR(ABS((Nn*Sxs-Sx^2)/(Nn*(Nn-1))))
5040  Sdevt=SQR(ABS((Nn*Sys-Sy^2)/(Nn*(Nn-1))))
5044  Sdevh=SQR(ABS((Nn*Szs-Sz^2)/(Nn*(Nn-1))))
5048  Sh=100*Sdevh/Have
5052  Sq=100*Sdevq/Qave
5056  St=100*Sdevt/Tave
5060  IF K=1 THEN 5084
5064  PRINT
5068  PRINT USING "11X,""DATA FILE:"",14A";File$
5072  PRINT
5076  PRINT USING "11X,""RUN Htube      SdevH   Qdp         SdevQ   Thetab SdevT""
"
5080  K=1
5084  PRINT USING "11X,DD,2(2X,D.3DE,1X,3D.2D),2X,DD.3D,1X,3D.2D";J,Have,Sh,Qave
,Sq,Tave,St
5088  GOTO 4940
5092  ASSIGN @File1 TO *
5096  PRINTER IS 1
5100  SUBEND
5104  SUB Coef
5108  COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
5112  BEEP
5116  INPUT "GIVE A NAME FOR CROSS-PLOT FILE",Cpf$
5120  BEEP
5124  INPUT "OUTPUT TYPE (0=q vs Dt, 1=h vs Dt, 2=h vs q)",Opo
5128  CREATE BDAT Cpf$,6
5132  ASSIGN @File TO Cpf$
5136  BEEP
5140  INPUT "SELECT (0=LINEAR,1=LOG(X,Y))",Ilog
5144  BEEP
5148  INPUT "ENTER OIL PERCENT (-1=STOP)",Bop
5152  BEEP
5156  INPUT "ENTER TUBE NUMBER (1, 2, 3, 4, OR 5)",Itn
5160  IF Bop<0 THEN 5176
5164  CALL Poly(Itn)
5168  OUTPUT @File;Bop,B(*)
5172  GOTO 5144
5176  ASSIGN @File TO *
5180  SUBEND
```

```
5184!
5188!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
5192!
5196  SUB Plot
5200  COM /Cply/ A(10,10),C(10),B(4),Nop,Iprnt,Opo,Ilog
5204  DIM Xy(17)
5208  INTEGER I1
5212  PRINTER IS 1
5216  BEEP
5220  Idv=1
5224  INPUT "LIKE DEFAULT VALUES FOR PLOT (1=Y(DEFAULT),0=N)?",Idv
5228  Opo=0
5232  BEEP
5236  PRINT USING "4X,""Select Option:"""
5240  PRINT USING "6X,""0  q versus delta-T(DEFAULT)"""
5244  PRINT USING "6X,""1  h versus delta-T"""
5248  PRINT USING "6X,""2  h versus q"""
5252  INPUT Opo
5256  BEEP
5260  INPUT "SELECT UNITS (0=SI(DEFAULT),1=ENGLISH)",Iun
5264  PRINTER IS 705
5268  IF Idv<>1 THEN
5272     BEEP
5276     INPUT "ENTER NUMBER OF CYCLES FOR X-AXIS",Cx
5280     BEEP
5284     INPUT "ENTER NUMBER OF CYCLES FOR Y-AXIS",Cy
5288     BEEP
5292     INPUT "ENTER MIN X-VALUE (MULTIPLE OF 10)",Xmin
5296     BEEP
5300     INPUT "ENTER MIN Y-VALUE (MULTIPLE OF 10)",Ymin
5304  ELSE
5308     IF Opo=0 THEN
5312        Cy=2
5316        Cx=2
5320        Xmin=1
5324        Ymin=1000
5328     END IF
5332     IF Opo=1 THEN
5336        Cy=2
5340        Cx=2
5344        Xmin=1
5348        Ymin=100
5352     END IF
5356     IF Opo=2 THEN
5360        Cy=2
5364        Cx=2
5368        Xmin=1000
5372        Ymin=100
5376     END IF
5380  END IF
5384  BEEP
5388  PRINT "IN;SP1;IP 2300,2200,8300,6800;"
5392  PRINT "SC 0,100,0,100;TL 2,0;"
5396  Sfx=100/Cx
5400  Sfy=100/Cy
5404  BEEP
5408  INPUT "WANT TO BY-PASS CAGE (1=Y, 0=NO(DEFAULT)",Ibp
5412  IF Ibp=1 THEN 5908
5416  PRINT "PU 0,0 PD"
5420  Nn=9
```

```
5424  FOR I=1 TO Cx+1
5428      Xat=Xmin*10^(I-1)
5432      IF I=Cx+1 THEN Nn=1
5436      FOR J=1 TO Nn
5440          IF J=1 THEN PRINT "TL 2 0"
5444          IF J=2 THEN PRINT "TL 1 0"
5448          Xa=Xat*J
5452          X=LGT(Xa/Xmin)*Sfx
5456          PRINT "PA";X,",0; XT;"
5460      NEXT J
5464  NEXT I
5468  PRINT "PA 100,0;PU;"
5472  PRINT "PU PA 0,0 PD"
5476  Nn=9
5480  FOR I=1 TO Cy+1
5484      Yat=Ymin*10^(I-1)
5488      IF I=Cy+1 THEN Nn=1
5492      FOR J=1 TO Nn
5496          IF J=1 THEN PRINT "TL 2 0"
5500          IF J=2 THEN PRINT "TL 1 0"
5504          Ya=Yat*J
5508          Y=LGT(Ya/Ymin)*Sfy
5512          PRINT "PA 0,";Y,"YT"
5516      NEXT J
5520  NEXT I
5524  PRINT "PA 0,100 TL 0 2"
5528  Nn=9
5532  FOR I=1 TO Cx+1
5536      Xat=Xmin*10^(I-1)
5540      IF I=Cx+1 THEN Nn=1
5544      FOR J=1 TO Nn
5548          IF J=1 THEN PRINT "TL 0 2"
5552          IF J>1 THEN PRINT "TL 0 1"
5556          Xa=Xat*J
5560          X=LGT(Xa/Xmin)*Sfx
5564          PRINT "PA";X,",100; XT"
5568       NEXT J
5572  NEXT I
5576  PRINT "PA 100,100 PU PA 100,0 PD"
5580  Nn=9
5584  FOR I=1 TO Cy+1
5588      Yat=Ymin*10^(I-1)
5592      IF I=Cy+1 THEN Nn=1
5596      FOR J=1 TO Nn
5600          IF J=1 THEN PRINT "TL 0 2"
5604          IF J>1 THEN PRINT "TL 0 1"
5608          Ya=Yat*J
5612          Y=LGT(Ya/Ymin)*Sfy
5616          PRINT "PD PA 100,",Y,"YT"
5620      NEXT J
5624  NEXT I
5628  PRINT "PA 100,100 PU"
5632  PRINT "PA 0,-2 SR 1.5,2"
5636  I1=LGT(Xmin)
5640  FOR I=1 TO Cx+1
5644      Xa=Xmin*10^(I-1)
5648      X=LGT(Xa/Xmin)*Sfx
5652      PRINT "PA";X,",0;"
5656      IF I1>=0 THEN PRINT "CP -2,-2;LB10;PR -2,2;LB";I1;""
5660      IF I1<0 THEN PRINT "CP -2,-2;LB10;PR 0,2;LB";I1,""
```

```
5664      I1=I1+1
5668  NEXT I
5672  PRINT "PU PA 0,0"
5676  I1=LGT(Ymin)
5680  Y10=10
5684  FOR I=1 TO Cy+1
5688      Ya=Ymin*10^(I-1)
5692      Y=LGT(Ya/Ymin)*Sfy
5696      PRINT "PA 0,";Y,""
5700      PRINT "CP -4,-.25;LB10;PR -2,2;LB";I1,""
5704      I1=I1+1
5708  NEXT I
5712  BEEP
5716  Id1=1
5720  INPUT "WANT USE DEFAULT LABELS (1=Y(DEFAULT),0=N)?",Id1
5724  IF Id1<>1 THEN
5728     BEEP
5732     INPUT "ENTER X-LABEL",Xlabel$
5736     BEEP
5740     INPUT "ENTER Y-LABEL",Ylabel$
5744  END IF
5748  IF Opo<2 THEN
5752     PRINT "SR 1,2;PU PA 40,-14;"
5756     PRINT "LB(T;PR -1.6,3 PD PR 1.2,0 PU;PR .5,-4;LBwo;PR .5,1;"
5760     PRINT "LB-T;PR .5,-1;LBsat;PR .5,1;"
5764     IF Iun=0 THEN
5768        PRINT "LB) / (K)"
5772     ELSE
5776        PRINT "LB) / (F)"
5780     END IF
5784  END IF
5788  IF Opo=2 THEN
5792     IF Iun=0 THEN
5796        PRINT "SR 1.5,2;PU PA 40,-14;LBq / (W/m;SR 1,1.5;PR 0.5,1;LB2;SR 1
.5,2;PR 0.5,-1;LB)"
5800     ELSE
5804        PRINT "SR 1.5,2;PU PA 34,-14;LBq / (Btu/hr;PR .5,.5;LB.;PR .5,-.5;
"
5808        PRINT "LBft;PR .5,1;SR 1,1.5;LB2;SR 1.5,2;PR .5,-1;LB);"
5812     END IF
5816  END IF
5820  IF Opo=0 THEN
5824     IF Iun=0 THEN
5828        PRINT "SR 1.5,2;PU PA -12,40;DI 0,1;LBq / (W/m;PR -1,0.5;SR 1,1.5;L
B2;SR 1.5,2;PR 1,.5;LB)"
5832     ELSE
5836        PRINT "SR 1.5,2;PU PA -12,32;DI 0,1;LBq / (Btu/hr;PR -.5,.5;LB.;PR
 .5,.5;"
5840        PRINT "LBft;SR 1,1.5;PR -1,.5;LB2;PR 1,.5,SR 1.5,2;LB)"
5844     END IF
5848  END IF
5852  IF Opo>0 THEN
5856     IF Iun=0 THEN
5860        PRINT "SR 1.5,2;PU PA -12,38;DI 0,1;LBh / (W/m;PR -1,.5;SR 1,1.5;LB
2;SR 1.5,2;PR .5,.5;"
5864        PRINT "LB.;PR .5,0;LBK)"
5868     ELSE
5872        PRINT "SR 1.5,2;PU PA -12,28;DI 0,1;LBh / (Btu/hr;PR -.5,.5;LB.;PR
 .5,.5;"
5876        PRINT "LBft;PR -1,.5;SR 1,1.5;LB2;SR 1.5,2;PR .5,.5;LB.;PR .5,.5;
```

```
LBF;"
5880      END IF
5884   END IF
5888   IF Idl=0 THEN
5892      PRINT "SR 1.5,2;PU PA 50,-16 CP";-LEN(Xlabel$)/2;"0;LB";Xlabel$;""
5896      PRINT "PA -14,50 CP 0,";-LEN(Ylabel$)/2*5/6;"DI 0,1;LB";Ylabel$;""
5900      PRINT "CP 0,0 DI"
5904   END IF
5908   Ipn=0
5912 Repeat: !
5916   Xll=1.E+6
5920   Xul=-1.E+6
5924   Icn=0
5928   BEEP
5932   Ok=1
5936   INPUT "WANT TO PLOT DATA FROM A FILE (1=Y(DEFAULT),0=N)?",Ok
5940   IF Ok=1 THEN
5944   BEEP
5948   INPUT "ENTER THE NAME OF THE DATA FILE",Dfile$(0)
5952   ASSIGN @File TO Dfile$(0)
5956   BEEP
5960   Npairs=20
5964   INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED(DEFAULT=20)",Npairs
5968   BEEP
5972   Itn=Itn+1
5976   INPUT "ENTER TUBE NUMBER (1, 2, 3, 4, OR 5)",Itn
5980   BEEP
5984   PRINTER IS 1
5988   INPUT "WANT DEFAULT SYMBOLS? (YES=0 (DEFAULT),NO=1)",Symb
5992   Sym=Itn+2
5996   IF Symb=0 THEN
6000      GOTO 6036
6004   END IF
6008   PRINT USING "4X,""Select a symbol:"""
6012   PRINT USING "6X,""1  Star      2  Plus sign"""
6016   PRINT USING "6X,""3  Circle    4  Square"""
6020   PRINT USING "6X,""5  Rombus"""
6024   PRINT USING "6X,""6  Right-side-up triangle"""
6028   PRINT USING "6X,""7  Up-side-down triangle"""
6032   INPUT Sym
6036   PRINTER IS 705
6040   PRINT "PU DI"
6044   IF Sym=1 THEN PRINT "SM*"
6048   IF Sym=2 THEN PRINT "SM+"
6052   IF Sym=3 THEN PRINT "SMo"
6056   FOR I=1 TO Npairs
6060   ENTER @File;Xy(*)
6064   IF Opo=0 THEN
6068      Ya=Xy(Itn-1)
6072      Xa=Xy(11+Itn)
6077   END IF
6080   IF Opo=1 THEN
6084      Ya=Xy(5+Itn)
6088      Xa=Xy(11+Itn)
6092   END IF
6096   IF Opo=2 THEN
6100      Ya=Xy(5+Itn)
6104      Xa=Xy(Itn-1)
6108   END IF
6112   IF Xa<Xll THEN Xll=Xa
```

```
6116  IF Xa Xul THEN Xul=Xa
6120  IF Iun=1 THEN
6124     IF Opo<2 THEN Xa=Xa*1.8
6128     IF Opo>0 THEN Ya=Ya*.1761
6132     IF Opo=0 THEN Ya=Ya*.317
6136     IF Opo=2 THEN Xa=Xa*.317
6140  END IF
6144  X=LGT(Xa/Xmin)*Sfx
6148  Y=LGT(Ya/Ymin)*Sfy
6152  Kj=0
6156  CALL Symb(X,Y,Sym,Icl,Kj)
6160  GOTO 6212
6164  IF Sym>3 THEN PRINT "SM"
6168  IF Sym<4 THEN PRINT "SR 1.4,2.4"
6172  IF Icl=0 THEN
6176     PRINT "PA",X,Y,""
6180  ELSE
6184     PRINT "PA",X,Y,"PD"
6188  END IF
6192  IF Sym>3 THEN PRINT "SR 1.2,1.6"
6196  IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0;"
6200  IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6;"
6204  IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,8;"
6208  IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8;"
6212  NEXT I
6216  PRINT "PU"
6220  BEEP
6224  Ilab=1
6228  INPUT "WANT TO LABEL? (1=Y(DEFAULT),0=N)",Ilab
6232  IF Ilab=1 THEN
6236     PRINT "SP0;SP2"
6240     BEEP
6244     IF Klab=0 THEN
6248        Xlab=65
6252        Ylab=85
6256        INPUT "ENTER INITIAL X,Y LOCATIONS",Xlab,Ylab
6260        Xtt=Xlab-5
6264        Ytt=Ylab+8
6268        PRINT "SR 1,1.5"
6272        PRINT "SM;PA",Xtt,Ytt,"LB      Tube    %   File"
6276        Ytt=Ytt-3
6280        PRINT "PA",Xtt,Ytt,"LB       No    Oil   Name"
6284        IF Sym=1 THEN PRINT "SM*"
6288        IF Sym=2 THEN PRINT "SM+"
6292        IF Sym=3 THEN PRINT "SMo"
6296        Klab=1
6300     END IF
6304     Kj=1
6308     CALL Symb(Xlab,Ylab,Sym,Icl,Kj)
6312     PRINT "SR 1,1.5;SM"
6316     IF Sym<4 THEN PRINT "PR 2,0"
6320     PRINT "PR 2,0;LB";Itn;""
6324     BEEP
6328     INPUT "ENTER BOP(0=DEFAULT)",Bop
6332     IF Bop<10 THEN PRINT "PR 3,0;LB";Bop;""
6336     IF Bop>9 THEN PRINT "PR 1.5,0;LB";Bop;""
6340     PRINT "PR 2,0;LB";Dfile$(0);""
6344     PRINT "SP0;SP1;SR 1.5,2"
6348     Ylab=Ylab-5
6352  END IF
```

```
6360  ASSIGN @File TO *
6364  Xll=Xll/1.2
6368  Xul=Xul*1.2
6372 ! GOTO 8040
6376  END IF
6380  PRINT "PU SM"
6384  BEEP
6388  Go_on=1
6392  INPUT "WANT TO PLOT A POLYNOMIAL (1=Y(DEFAULT),0=N)?",Go_on
6396  IF Go_on=1 THEN
6400     BEEP
6404     PRINTER IS 1
6408     INPUT "WANT DEFAULT LINE TYPE? (YES=0 (DEFAULT),NO=1)",Ln
6412     Ipn=Itn
6416     IF Ln=0 THEN
6420        GOTO 6448
6424     END IF
6428     PRINT USING "4X,""Select line type:"""
6432     PRINT USING "6X,""0      Solid line"""
6436     PRINT USING "6X,""1      Dashed"""
6440     PRINT USING "6X,""2,,,5 Longer line - dash"""
6444     INPUT Ipn
6448     PRINTER IS 705
6452     BEEP
6456     Ilog=1
6460     INPUT "SELECT (0=LIN,1=LOG(DEFAULT))",Ilog
6464     Iprnt=1
6468     CALL Poly(Dfile$(*),Npairs,Itn)
6472     FOR Xx=0 TO Cx STEP Cx/200
6476         Xa=Xmin*10^Xx
6480         IF Xa<Xll OR Xa>Xul THEN 6572
6484         Icn=Icn+1
6488         Pu=0
6492         IF Ipn=1 THEN Idf=Icn MOD 2
6496         IF Ipn=2 THEN Idf=Icn MOD 4
6500         IF Ipn=3 THEN Idf=Icn MOD 8
6504         IF Ipn=4 THEN Idf=Icn MOD 16
6508         IF Ipn=5 THEN Idf=Icn MOD 28
6512         IF Idf=1 THEN Pu=1
6516         Ya=FNPoly(Xa)
6520         IF Ya<Ymin THEN 6572
6524         IF Iun=1 THEN
6528            IF Opo<2 THEN Xa=Xa*1.8
6532            IF Opo>0 THEN Ya=Ya*.1761
6536            IF Opo=0 THEN Ya=Ya*.317
6540            IF Opo=2 THEN Xa=Xa*.317
6544         END IF
6548         Y=LGT(Ya/Ymin)*Sfy
6552         X=LGT(Xa/Xmin)*Sfx
6556         IF Y<0 THEN Y=0
6560         IF Y>100 THEN GOTO 6572
6564         IF Pu=0 THEN PRINT "PA",X,Y,"PD"
6568         IF Pu=1 THEN PRINT "PA",X,Y,"PU"
6572       NEXT Xx
6576     . PRINT "PU"
6580  END IF
6584  BEEP
6588  INPUT "WANT TO QUIT (1=Y,0=N(DEFAULT))",Iqt
6592  IF Iqt=1 THEN 6600
```

```
6596  GOTO 5316
6600  PRINT "PU PA 0,0 SP0"
6604  SUBEND
6608!
6612!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6616!
6620  SUB Symb(X,Y,Sym,Icl,Kj)
6624  IF Sym>3 THEN PRINT "SM"
6628  IF Sym<4 THEN PRINT "SR 1.4,2.4"
6632  Yad=0
6636  IF Kj=1 THEN Yad=.8
6640  IF Icl=0 THEN
6644     PRINT "PA",X,Y+Yad,""
6648  ELSE
6652     PRINT "PA",X,Y+Yad,"PD"
6656  END IF
6660  IF Sym>3 THEN PRINT "SR 1.2,1.6"
6664  IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0;"
6668  IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6,"
6672  IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,8;"
6676  IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8;"
6680  IF Kj=1 THEN PRINT "SM;PR 0,-.8"
6684  SUBEND
6688!
6692!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6696!
6700  SUB Fixup
6704! FILE: FIXUP
6708!
6712  DIM Emf(34),Amp(11),Volt(4),Ldtc(4)
6716  BEEP
6720  INPUT "OLD FILE TO FIXUP",D2file$
6724  ASSIGN @File2 TO D2file$
6728  D1file$="TEST"
6732  CREATE BDAT D1file$,60
6736  ASSIGN @File1 TO D1file$
6740  ENTER @File2;Nrun,Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
6744  OUTPUT @File1;Nrun,Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
6748  FOR I=1 TO Nrun
6752      ENTER @File2;Told$,Emf(*),Volt(*),Amp(*)
6756      IF I=1 THEN 6764
6760      OUTPUT @File1;Bop,Told$,Emf(*),Volt(*),Amp(*)
6764  NEXT I
6768  ASSIGN @File2 TO *
6772  ASSIGN @File1 TO *
6776! RENAME "TEST" TO D2_file$
6780  BEEP 2000,.2
6784  BEEP 4000,.2
6788  BEEP 4000,.2
6792  SUBEND
6796!
6800!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6804!
6808  SUB Move
6812! FILE NAME: MOVE
6816!
6820  DIM A(66),B(66),C(66),D(66),E(66),F(66),G(66),H(66),J(66),K(66),L(66),M(66
)
6824  DIM N(66),Emf(34),Volt(2),Amp(11),Ldtc(4)
6828  BEEP
```

```
6832  INPUT "OLD FILE TO MOVE",D2_file$
6836  ASSIGN @File2 TO D2_file$
6840  ENTER @File2;Nrun,Told$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
6844  FOR I=1 TO Nrun
6848      ENTER @File2;Told$
6852      ENTER @File2;A(I),B(I),C(I),D(I),E(I),F(I),G(I),H(I),J(I),K(I),L(I),M(
I),N(I)
6856      ENTER @File2;Emf(*),Volt(*),Amp(*)
6860  NEXT I
6864  ASSIGN @File2 TO *
6868  BEEP
6872  INPUT "SHIFT DISK AND HIT CONTINUE",Ok
6876  BEEP
6880  INPUT "INPUT BDAT SIZE",Size
6884  CREATE BDAT D2_file$,Size
6888  ASSIGN @File1 TO D2_file$
6892  OUTPUT @File1;Nrun,Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
6896  FOR I=1 TO Nrun
6900      OUTPUT @File1;Told$
6904      OUTPUT @File1;A(I),B(I),C(I),D(I),E(I),F(I),G(I),H(I),J(I),K(I),L(I),M
(I),N(I)
6908      OUTPUT @File1;Emf(*),Volt(*),Amp(*)
6912  NEXT I
6916  ASSIGN @File1 TO *
6920! RENAME "TEST" TO D2_file$
6924  BEEP 2000,.2
6928  BEEP 4000,.2
6932  BEEP 4000,.2
6936  PRINT "DATA FILE MOVED"
6940  SUBEND
6944!
6948!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6952!
6956  SUB Purg
6960  BEEP
6964  INPUT "ENTER FILE NAME TO BE DELETED",File$
6968  PURGE File$
6972  GOTO 6960
6976  SUBEND
6980!
6984!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6988!
6992  SUB Comb
6996! FILE NAME: COMB
7000!
7004  DIM Emf(34),Volt(2),Amp(11),Ldtc(4)
7008  BEEP
7012  INPUT "OLD FILE TO FIXUP",D2_file$
7016  ASSIGN @File2 TO D2_file$
7020  D1_file$="TEST"
7024  CREATE BDAT D1_file$,30
7028  ASSIGN @File1 TO D1_file$
7032  ENTER @File2;Nrun,Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
7036  IF K=0 THEN OUTPUT @File1;Nrun,Date$,Ldtc(*),Itt,Bop,Nht,Natp,Nrt,Corr
7040  FOR I=1 TO Nrun
7044  ENTER @File2;Bop,Told$,Emf(*),Volt(*),Amp(*)
7048  OUTPUT @File1;Bop,Told$,Emf(*),Volt(*),Amp(*)
7052  NEXT I
7056  ASSIGN @File2 TO *
7060! RENAME "TEST" TO D2_file$
```

```
7064  BEEP 4000,.2
7068  BEEP
7072  Oka=1
7076  INPUT "WANT TO ADD ANOTHER FILE (1=Y,0=N(default))?",Oka
7080  IF Oka=1 THEN
7084  K=1
7088  BEEP
7092  INPUT "GIVE NEW FILE NAME",Nfile$
7096  ASSIGN @File2 TO Nfile$
7100  GOTO 7032
7104  END IF
7108  ASSIGN @File2 TO *
7112  SUBEND
7116!
7120!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
7124!
7128  SUB Readplot
7132  DIM Qdp(5),Htube(5),Thetab(5)
7136  PRINTER IS 701
7140  INPUT "ENTER FILE NAME",File$
7144  INPUT "ENTER THE NUMBER OF DATA PAIRS",Nrun
7148  ASSIGN @File1 TO File$
7152  FOR I=1 TO Nrun
7156      ENTER @File1;Qdp(*),Htube(*),Thetab(*)
7160      PRINT Qdp(*)
7164      PRINT
7168      PRINT Htube(*)
7172      PRINT
7176      PRINT Thetab(*)
7180      PRINT
7184      PRINT
7188  NEXT I
7192  SUBEND
```

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